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STUDIES OF THE USE OF PERVIOUS FENCE FOR STREAMBANK REVETMENT

by

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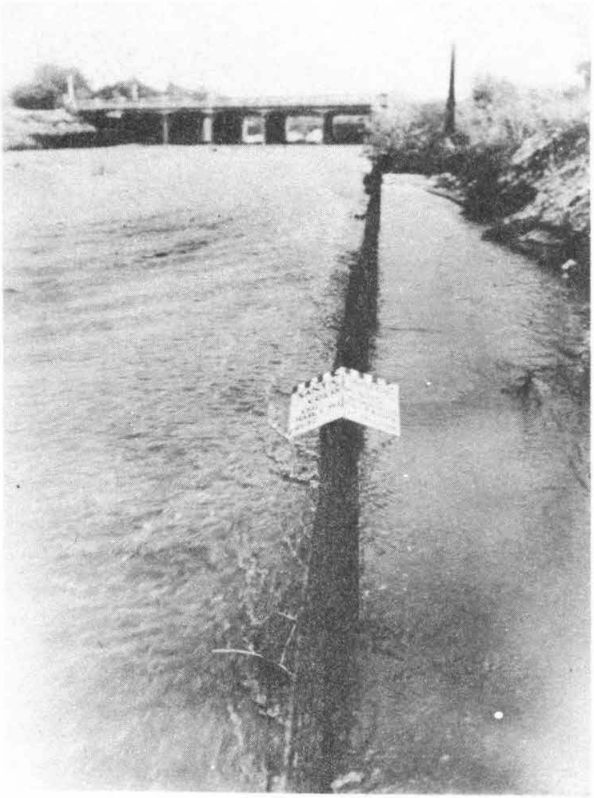

Frontispiece - FLOW ALONG CHANNELS AND BANK SIDES OF FENCE

Looking downstream along rail and wire fence. Note standing waves off debris on fence and sediment deposits upstream from groin in right background. Flow depth in channel is about 1 ft and total flow about 200 cfs.

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I. INTRODUCTION AND ACKNOWLEDGEMENTS

This report contains the results of a field and laboratory study of a pervious fence used as revetment for the banks of an open channel carrying sediment laden flow. The study was made at the Cooperative Hydraulic Laboratory of the Soil Conservation Service (U.S. Department of Agriculture) and the California Institute of Technology at Pasadena, California during two periods: October 1944 to May 1945 and June 1946 to June 1947.

The study was initiated under Dr. M. L. Nichols, Chief of Research of the Soil Conservation Service, Washington, D.C. by Mr. Carl Brown, Sedimentation Specialist of the S.C.S., Washington, D.C. and Mr. Don Williams, Flood Control Engineer of the Portland, Oregon office of the S.C.S.

The assistance of the engineers and foreman of the Los Angeles County (California) Flood Control District under the general supervision of Mr. H.E. Hedger, Chief Engineer is hereby gratefully acknowledged. The bulk of the data on the design, construction and behavior of the field installations as well as many photographs and prints were collected from them through the efforts of Mr. W. J. Manetta, Division Engineer and Mr. G. V. Dittman, Construction Superintendent.

Mr. A. A. Beard and Mr. J.A. Bradley, Consulting Engineer and Flood Control Engineer respectively of the Orange County (California) Flood Control District, and members of the City of Pasadena (California) Water Department under Mr. M. S. Jones, Chief Engineer, all aided the investigation by conducting inspections of their installations and by making available their records. Their assistance is hereby gratefully acknowledged.

The laboratory test apparatus was designed by and erected under the direction of Dr. H.A. Einstein, Hydraulic Engineer of the Soil Conservation Service, who also conducted the experiments during the first period of the study. The tests during the second period as well as most of the field investigations were conducted by Mr. J.T. O'Brien, Hydraulic Engineer of the S.C.S. Mechanical, photographic, and other services were performed by the regular staff of the Cooperative Laboratory.

This report was prepared as a project of the Hydrodynamics Laboratory of the California Institute of Technology under contract with the Soil Conservation Service of the U.S. Department of Agriculture.

All of the work was under the direct and active supervision of Dr. Vito A. Vanoni, Associate Director of the Hydrodynamics Laboratory.

II. OBJECT OF THE STUDY

A pervious vertical fence has been used as a form of stream bank revetment for at least 25 years in various parts of the United States and particularly in Southern California. While the cost of materials has always been considerable, the ease with which the fence can be constructed, and the stolid, assured appearance it gives, have made it very popular. However, notwithstanding the many miles of installations there does not seem to be unanimous agreement as to the real merit of the fence as an aid in reducing the bank scour. The skeptical attitude of some hydraulic engineers may be summed up in their specifications for a good revetment fence as "one that can be quickly and easily removed from the stream channel during flood periods to avoid damage to the fence."

Because of such doubtful recommendations, the Cooperative Laboratory was requested to collect and study data on field installations and to run experiments in the laboratory to determine if possible the effectiveness of a fence used as a stream bank revetment.

The study was concerned mainly with the performance of a vertical pervious fence when installed in the bed of an earthen channel but not in contact with the banks nor subject to earth pressures. This performance was measured by the protection given the channel banks against the forces set up by the sediment-laden flowing water. It was necessary to include in the study the performance of such supplements to the fence as debris lodged on it, vegetation and groins on the banks behind it, and stabilizers for the channel bed since the fence usually functions in a channel which contains some or all of these.

Division of the work was made into a field investigation and a laboratory investigation so designed that one supplemented the other. The object of the field investigation was to collect data on the design and behavior of revetment fences in actual installations. This, of course, included many fences in curved as well as tangent sections of channel.

However in the laboratory investigation it was decided to limit the study to that of a fence and its supplements installed in a tangent section of a channel with erodible bed and banks discharging sediment-laden water. It was realized that the measurement of all the pertinent hydraulic elements necessary for a fully quantitative study of the problem would be extremely difficult. Therefore, it was decided their measurement would not be attempted and that rather the revetments would be evaluated qualitatively on the basis of their over-all effectiveness in protecting the banks of the laboratory channel. The time necessary for the flowing water to erode the revetted banks of the laboratory channel a particular amount was the basic criterion used to determine the effectiveness of the various revetments tested.

From the field and laboratory studies, it was hoped certain qualitative conclusions could be made which would indicate the likely effectiveness of a fence and its supplements in an open channel.

III. FIELD STUDIES

A. Introduction

The design of a pervious stream bank revetment has been made generally by cut-and-try methods during at least the quarter century of its active use. This pragmatic solution is reflected in the older composite revetments in Los Angeles County, California, which show the original fence with the attachments and modifications that have been made as the result of flood damage.

To obtain data on the construction and behavior of a pervious fence, many field installations in Los Angeles and Orange Counties were inspected in the dry season and during the small run-off period of the 1946-47 water year. The process of maintenance of a revetted channel of this type is a continuous one so that in many cases the flood damage of previous storms had long been repaired and the evidence of its behavior obliterated. Thus it was necessary to study some of the records and pictures taken of the channel control operations and to talk with the engineers, foreman, and patrolmen who worked and observed during the periods of flow. Projects under construction were visited to obtain an understanding of the current construction methods and machines used.

A pervious channel revetment permits part of the water in the channel to infiltrate into the surrounding ground. It was noted that there is a growing need for a reliable, well-designed, pervious form of complete channel stabilization which will permit the conservation of a large part of surface runoff in the form of ground water since this is becoming an economic necessity. In one particular watershed visited, the landowners have successfully prevented the complete revetting of an open channel with an impervious concrete lining for which funds had been appropriated by appealing to the need for a channel control which would permit the maximum amount of the flow in the channel to infiltrate into the ground where it could be used for domestic and agricultural purposes.

The majority of the pervious fence revetments in the area inspected are constructed of pipe to which wire fencing is fastened. This construction is used because of the relative ease with which the materials (largely salvaged) may be procured and the simplicity of installation. Therefore, the discussions here are devoted mainly to the pipe and wire fence. Several views of such a fence are given in Fig. 1, although the welded wire fencing illustrated in the figure is not the preferred type, which is of twisted wire (Elwood fencing or the equivalent).

B. Design Considerations

The conception of a pervious fence as a temporary, high maintenance, form of a stream bank revetment has persisted through the many years of its use; therefore, its design has not been given serious study by those familiar with hydrodynamic phenomena. Rather, the design has been founded upon the intuitive reasoning particularly of construction and maintenance personnel, and based upon the stipulation that in most cases, relatively cheap and even used materials will be used in the construction.

However, certain basic concepts or rationalizations as to the behavior of the flow in an open channel seem well accepted by those in responsible charge. These may be summed up as follows:

a. In a particular channel with a given discharge there is a specific amount of suspended and bed load which the flowing water can transport. This is called "capacity load" and when the stream is so loaded, it is said to be in balance.

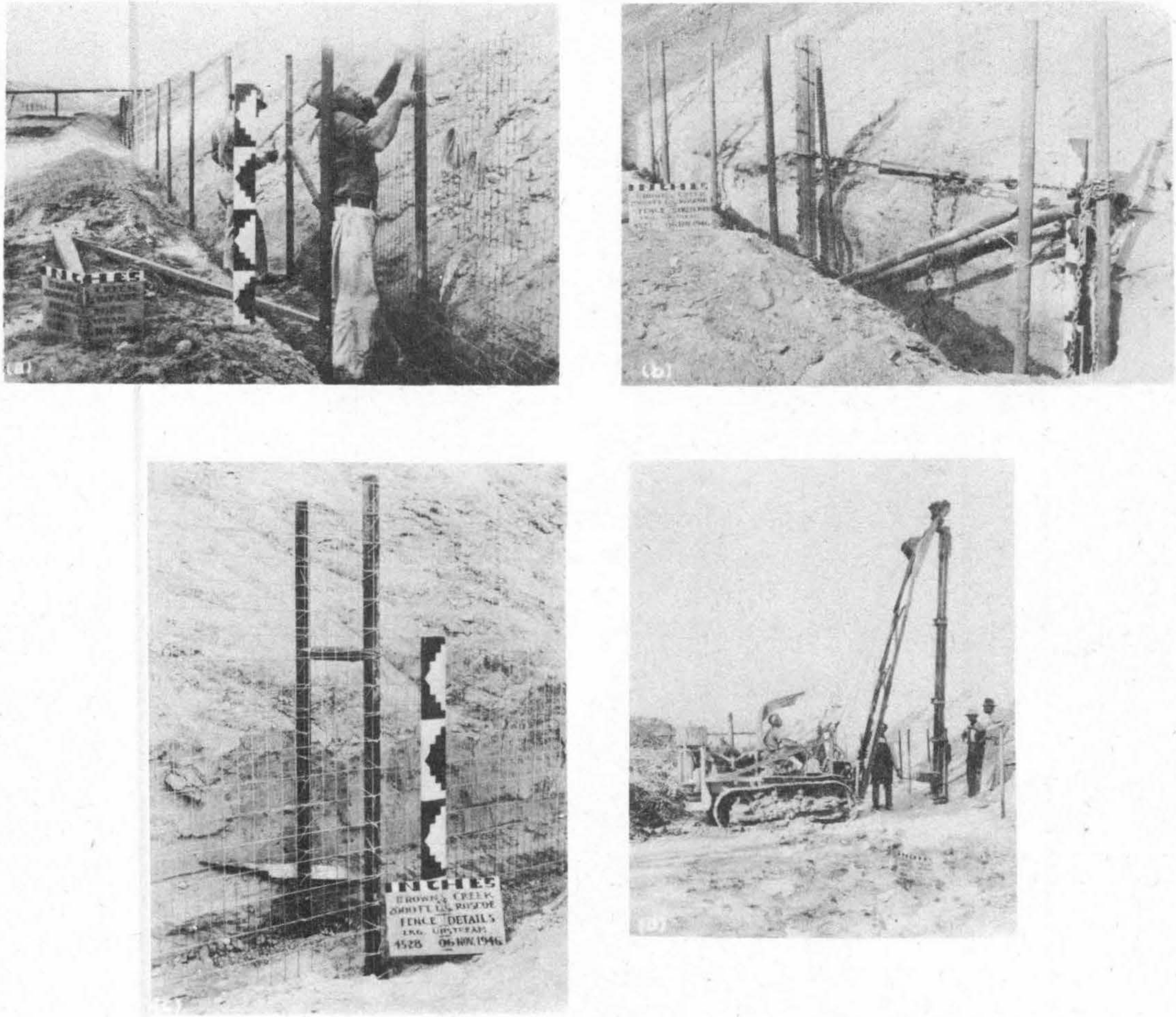

Fig. 1 - PIPE AND WIRE REVETMENT UNDER CONSTRUCTION

Pipe is 2 1/4 in. diameter boiler tubes and fencing is 6 ft wide welded wire with 2-in. by 4 in. openings. (a) Looking upstream at inside of double fence. Note brace. Workmen are tieing fencing to pipes. (b) Fencing being stretched. Braces will be left in place. (c) Completed fence. Trench will be backfilled. (d) Pipes (boiler tubes) being driven with portable pile driver. Hammer weighs about 500 lbs.

b. If its load is not proper the channel will be distorted by the flowing water from its original shape until a proper shape is obtained. That is if the stream is not carrying a capacity load it may erode the channel and flatten the grade.

c. Stabilization of the channel vertically or laterally may cause a dynamic flow reaction in the unaltered direction. For instance, if the grade of the stream is stabilized the stream may widen.

d. Flowing water produces certain forces on the walls of the channel which confine it, and on revetments and the like which obstruct it. For instance, groins which obstruct the flow are subject to considerable overturning and undercutting forces.

These concepts are stated and restated (although not in these words) orally and in the literature studied and it is with an appreciation of them that most of the recent revetment layouts seem to be made. However, no formulae stating the relations between the variables involved and specifically applicable to the general design of a previous revetment were found. For instance if the hydraulic forces acting on a fence were known, there would be no difficulty in designing the fence to resist overturning. However, these hydraulic forces could not be predicted with confidence.

The fence proper was originally regarded as a form of additional roughness which would serve to reduce the mean velocity of the stream flow by reducing that near the banks. However, with a fence pervious enough to resist the forces imposed upon it without elaborate structural supports, it was soon realized that the increase in roughness was not as considerable as expected for the banks when protected by such a fence were consistently scoured. However, no sound experimental comparative data on the behavior of a channel with and without fence revetment was obtained during the field studies so the effect of a fence on the rate of scour is not known.

Field observations indicated that the flow in an open channel during floods was usually far from steady and that even when it approached this condition closely there was a continual fluctuation of the water level which was manifest along the banks as a rise and fall of the water surface about a mean level similar to the action of waves along a beach. This continual fluctuation or lapping undermined the channel bank and caving resulted. It also was noted that when the flow was directed towards the fence (as in some curved sections) there was considerable turning of the flow away from the wall provided the mesh of the fencing was small enough or the usual substitute in the form of brush between a double fence was used. Finally it became increasingly apparent that some form of a guide wall was necessary in a debris-laden open channel particularly to force the larger debris away from the banks and into the main channel where it would be less likely to plug the channel and cause filling and that a flexible fence was well adapted for such use.

Therefore the recent concepts consider the fence necessary in an open channel:

a. To deflect the main flow away from the banks (as in curved sections)

b. To dampen the waves and eddies generated in the channel by:

(1) the normal fluctuations in the water level,

(2) the non uniformity of the channel bottom (manifest as sand waves)

(3) obstructions such as groins, piers, etc.

c. To serve as a wall to guide debris away from the bank.

The deflecting and damping functions of the fence usually require that its perviousness be a minimum, which would mean the use of relatively fine mesh fencing or of ordinary fencing with the perviousness reduced by the inclusion of brush between the openings. Its function as a guide wall mainly for floating debris, however, can be served by fencing with relatively large openings.

As mentioned previously, no formal procedures for the design of a fence revetment were encountered. Therefore, in lieu of these certain accepted layouts for the fence and its supplements are presented in the following section together with some comment as to their applicability.

Special climatic factors such as ice-laden flows, prolific natural vegetation, different land use practices and the like may dictate that the layouts presented not be applied without modification in climatic regions which differ from that of Southern California. However, there should be enough information of a general nature in the material presented to provide a guide for the construction of pervious channel revetments in various climates.

C. Construction Details for a Fence and its Supplements

1. Fence

The pertinent details for the layout of a fence are given in Fig. 2. The fence is always built vertically with the inside about 1/2 ft. from the toe of the sloping bank in a new channel or the nearly vertical banks of some old entrenched channel. The alignment of the fence should contain no abrupt changes; therefore the sharp meanders in the older channels are usually isolated through a more gradual alignment for the new channel as defined by the fence. Its height is usually such that it will not be overtopped by the design flow, although in some cases overtopping is accepted especially when the peaks of the design hydrograph are of short duration. The height of the fence for the type of construction being discussed usually does not exceed 8 ft.

Generally, single fences are used in the tangent sections of a stream and on the inside of curves and double fences are used on the outside of curves and upstream and downstream from grade stabilizers. Usually both banks of a stream are protected. The fencing found best suited, at least in Southern California, is one composed of No. 12 and No. 14 gage (0.11" and 0.08" diameter) wires, Elwood fencing of Spec. I or the equivalent, in which the wires are woven and twisted together but not welded in the pattern of an isosceles triangle with a 2" base and 4" altitude as shown in Fig. 2. Fencing of the same type but with the base of the triangle increased to 4" is preferred but not always used (the 2" x 4" pattern is used instead) for the stream side fence of the double fences.

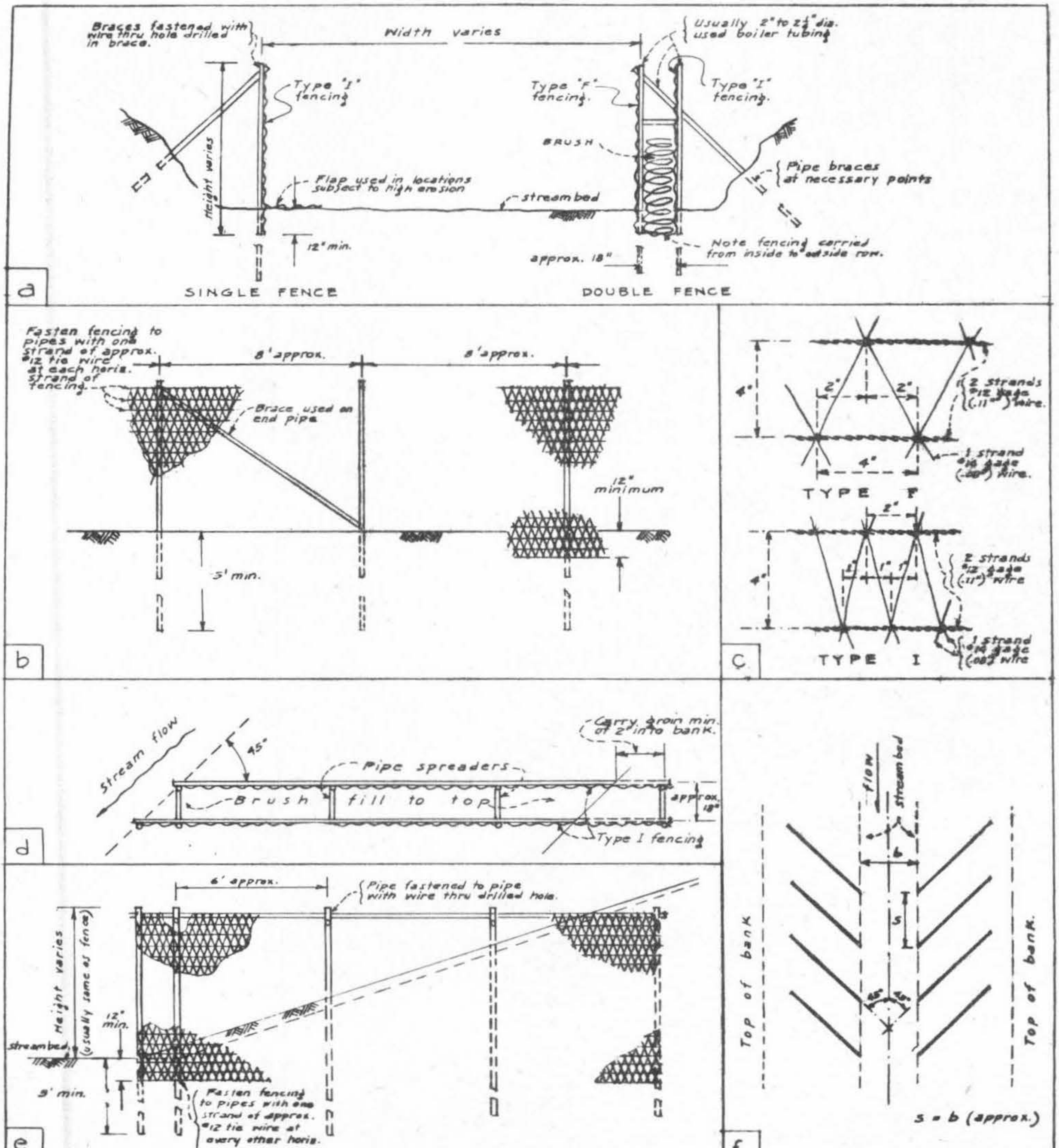

Fig. 2 - PIPE AND WIRE FENCE AND GROIN CONSTRUCTION DETAILS

Sketches of typical details. (a) Section through a single and double fence. Note that fencing is carried below stream bed. (b) Elevation of fence. Note end brace. (c) Detail of Elwood fencing. (d) Plan view of groin. Note brush. (e) Elevation of groin. (f) Plan view of groin layout.

The uprights are usually of 2" to 3" diameter used boiler pipe or light weight rails spaced about 8 ft. center to center. These are driven into the bed with either a sledge hammer or pile driver to a depth considered sufficient for stability after which the fencing is stretched and fastened to the stream side of the uprights with about No. 12 gage wire. If a double fence is needed a second row of pipes is driven opposite and parallel to the first row and spacers of pipe about 1 1/2 ft. long are inserted between the pipes of the inside and outside rows and wired to the uprights. Finally, lateral braces of pipe are driven into the stream bank to a depth proper for stability and wired to the uprights through holes drilled in both the upright and brace. Lateral braces are usually used at every other upright on single fences and those in a tangent section and inside of curves while braces are used at every upright on fences on the outside of curves and those double fences in which the space between them has been filled with brush.

It is expected that even in a channel with a generally stable grade there will be some local periodic lowering of the bed when the sand waves associated with the bed load movement pass a particular point. Therefore the fencing is usually carried at least 1 ft. into the existing channel bed as noted in Fig. 2. This extension is also built as some indemnity against miscalculation of the over-all flood position of the channel bottom. Usually all the lower one-half of the space between the double fence is filled with brush or even tin cans and sometimes brush is placed between the fence and bank where the growth of vegetation is usually encouraged.

It is important that all pipes be driven to a sufficient depth and properly braced laterally so that overturning of the completed fence does not occur. Calculation of the overturning moment should be made by the usual means after an estimate of the forces involved has been made.

2. Groins

The arrangement of a system of groins in a straight channel is shown in Fig. 2-f. It will be noted that the axes of any two groins, located opposite each other and on opposite banks, if extended, will intersect at a point along the centerline of the main channel at an acute angle with the flow of 45°. Note that all groins are pointed downstream. These are not intended to trap sediment[1] but only to reduce the scour of the banks by forcing the flow away from the banks.

The groins pointing downstream at 45° with the flow are considered to induce smaller amounts of local scour than those inclined at larger angles.[2] Groins at angles less than 45° are not generally used on the smaller streams in Southern California.

The distance between groins[3] is not well established but at one of the newer installations visited, it was found to be 50 ft. in a 50 ft. wide channel. This is a ratio of channel width to spacing of 1 to 1.

Figure 3 shows a groin of the permeable type, rectangular in shape with the major plane vertical at an attitude of 45° with the flow direction. The top is horizontal at an elevation slightly above the level of the design flow and the bottom is set 4 to 5 ft. down into the stream bed. Both ends of the groin are vertical with the stream end terminated at the toe of the sloping bank. The rails, pipes, or timbers which form the framework for the groin are driven in two parallel rows into the bottom of a trench previously dug into the bank. The space between the uprights is about 1 1/2 ft. Wire fencing is installed along both rows of uprights or on both sides of a post if used. The space between the fencing is completely filled with brush and the trench is backfilled to the slope of the bank. A cross section through the channel

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[1] Engles (1) reports from experiments with groins intended primarily to cause deposition that groins directed upstream are preferable.

[2] Saveson and Overholt (2) report that deflectors (groins) set at 45° with the bank and extending downstream were most effective in causing deposition and sandbar cutting. Other angles tried were 90° and 60°.

[3] Ehrenberger (3) reports from experiments concerned chiefly with the determination of the directions of flow between spur dikes (groins) extending above high water that he considers that the directions of the flow between dikes (groins) are dependent not on the proportions of regulated channel width to groin spacing but on the proportion of groin length to the distance between groins. This ratio is most favorable between 1:1 and 1:2 because with that arrangement only single eddies develop between groins.

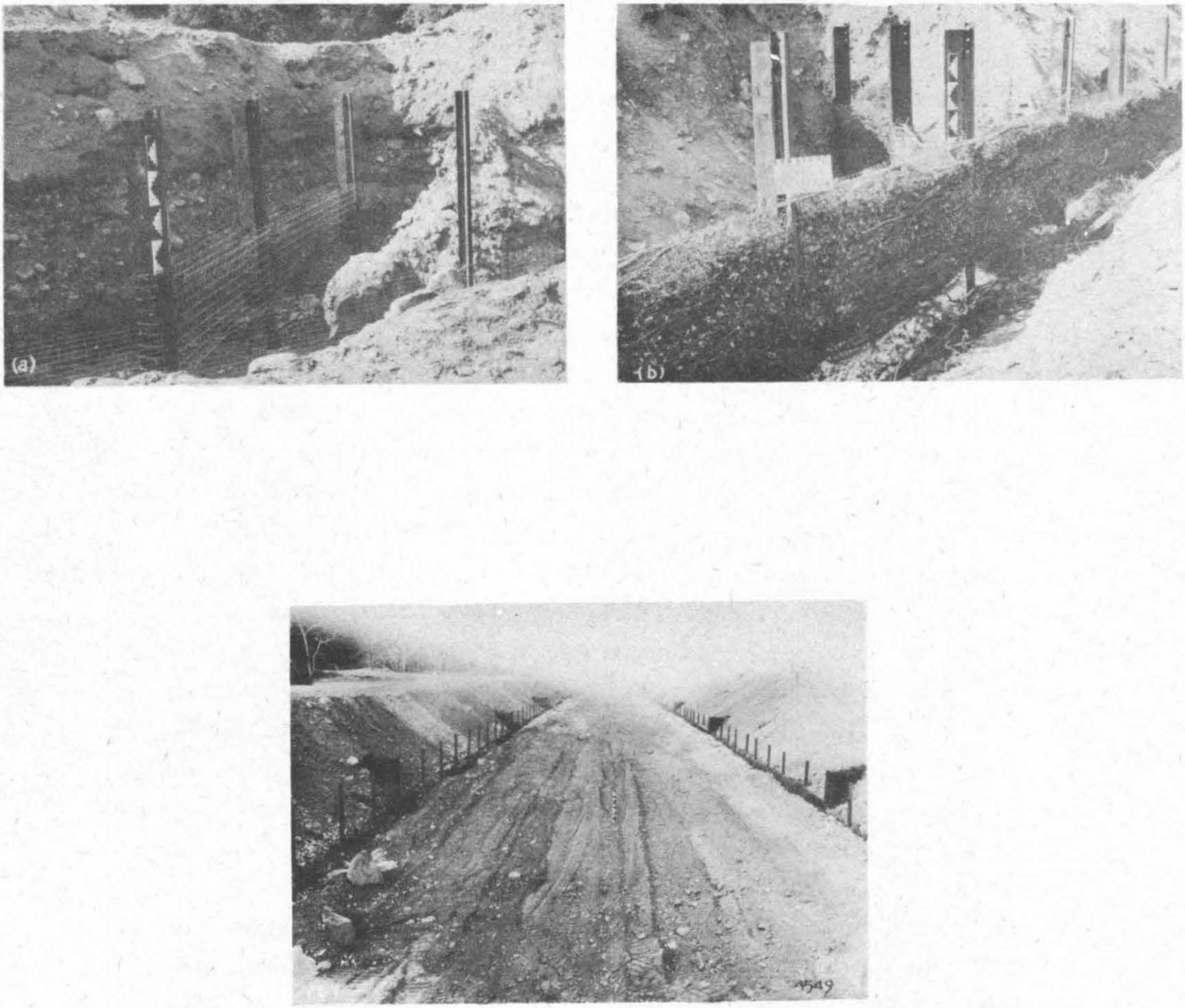


Fig. 3 - DETAILS OF GROIN

Used with rail and wire fence. Angle is 45° with flow. Groins point downstream. (a) Framework. Elwood wire used on groin. Top of welded wire on fence is about at channel bottom. Note timbers bolted to rails. (b) Brush placed between fencing. Note depth to which it is carried. (c) Looking upstream at partially completed channel. Width is about 50 ft and groins are spaced 50 ft. Note cables slung between rails. These are intended to help hold fence together should parts be undercut.

at the stream end of a pair of groins is U-shaped, with the channel bed as the horizontal portion and the pervious wire and brush groins as the vertical sides.

The groins are intended to obstruct at least partially, the stream flow and to force it either to percolate through the groin or flow around the stream side. Such groins are usually used in combination with a wire fence placed along the toe of the sloping bank as shown in Fig. 3-c.

In regard to groins in a channel the statements of Schoklitsch (4) on the subject are of interest. A pertinent quote is as follows:

"Groins may be normal to the current, or may be inclined somewhat upstream or downstream. All types contract the channel to the project width but their accretionary action differ. Experience has taught that the type inclined upstream is the most effective in causing the bays between groins to fill up. Due to the backing up of the water which groins cause, a pool forms at the head of the groin in a manner similar to that at bridge piers. The pool is deepest with the groin inclined upstream. The contraction of the channel by spur dikes results in a lowering of the river bed between the limits of the proposed channel. The head and part of the groin near the head must, accordingly, be constructed either so that it cannot be endangered by the pool or so it can adjust itself to the changes in the configuration of the bed and finally cover the bottom of the pool. The pool is deeper, the greater the slope of the head of the groin is. A slow circling motion is imparted to the water in the bay between the groins, and detritus and suspended matter are deposited there. The flanking of the groin at the root is prevented by keying it carefully into the shore about 10 to 15 ft. .... The crest (of the groin) must never be higher than the bank, as otherwise the river may cut around the bank end of the dike during high water. The downstream side or toe of the overflow groins must be provided with an apronto prevent undermining by the overfalling water. The non-overflow type (groin) is more effective in causing a filling up of the bays between spurs, but results in deeper pools at the channel end..... There are no reliable rules for the spacing of groins..... Groins have not proved satisfactory in sharp bends, and training walls are used instead. In straight stretches, the groins are always arranged so that the axes of opposite spurs shall intersect in the middle of the channel."

3. Grade Stabilizers

The determination of a stable flood grade for the channel is necessary before the location of the stabilizers in the channel can be made. This slope is calculated using current hydrologic techniques which include the study of the records of performance of the channel or of similar channels. As yet methods for the determination of the channel flood slope as outlined by Einstein (5) using the mechanical characteristics of the bed load as the major variable are not generally used. The calculation of the flood slope is usually a difficult matter and often the results are not fully reliable.

If a reliable flood slope can be calculated, the stabilizers are located on it such that a line through their crests will be at the calculated slope. When the calculated flood slope is not considered fully reliable a conservative method of location is used namely to locate the grade stabilizers on the grade selected such that the crest of any stabilizer is above the toe of that immediately upstream from it. In deeply entrenched channels where the height of the banks is excessive, the elevation of the crests of the stabilizers is adjusted so that filling will occur behind them before the stable grade is reached and thereby the height of the channel banks will be reduced. Where this is not necessary, the stabilizer crests are placed close to the existing bed but at the flood grade selected.

Figure 4 shows a grade stabilizer designed mainly of sheet steel and railroad rails. The rails are driven about 25 ft. into the channel bed and the sheet steel facing is carried about 15 ft. below the crest and into the bank. A small stilling basin to dampen the overfall is usually built of field stone and mortar or in some cases a brush mat is used.

The stabilizer design presented, even though admittedly inadequate as a true dam, is expensive (cost was about $3000 in 1947) to construct. Many cheaper improvisations even on this design are constructed using pipe, wire, rocks, cribbed rocks and timbers etc. in the hope that they

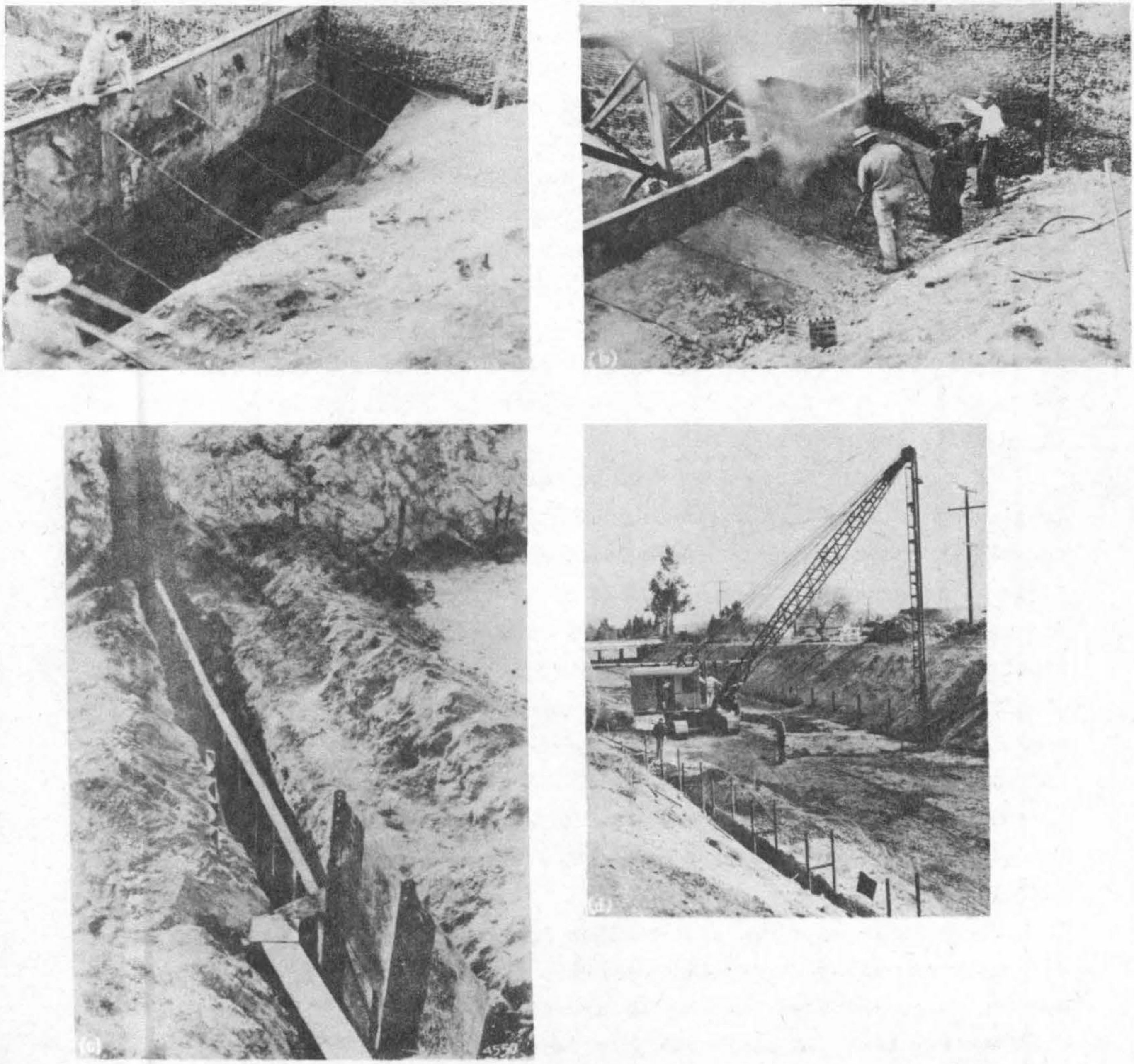


Fig. 4 - SHEET STEEL GRADE STABILIZER

Stabilizers shown are constructed basically of 1/4 in. thick sheet steel and rails. (a) Looking at upstream face. Observer's hands rest on crest of stabilizer. Note cables tied to dead men as restraints against overturning. (b) Backfilling after repairing scour under stabilizer induced by flow through a gopher hole. (c) Looking at upstream face. Crest is pitched 1/2 ft in 18 ft (half width of channel). (d) Drag line using 2000 lb hammer to drive rails. Grade stabilizer to be erected here. Fence in foreground has yet to be braced laterally.

will serve until it is possible to construct something better or in many cases until the channel can be completely lined with a pervious material. Photographs of some of these are shown in Fig. 5.

Certain agencies have found it worth while, even on small streams, to build concrete stabilizers that are properly designed complete with stilling basins. A few performance records available indicate that these dams are satisfactory, but the financial investment involved is in many cases greater than most agencies charged with flood control on small streams consider they can afford.

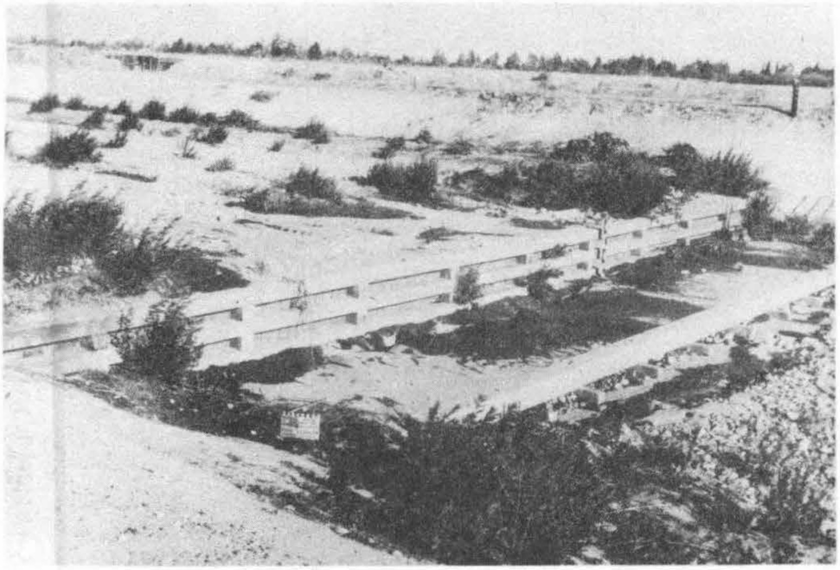
However, it must be realized that no matter how temporary a structure is rated, it is still subject to the same imposed forces as the permanent structure. Also the execution of a stable design, with the salvaged and used construction materials which sometimes form a temporary structure, is usually more difficult than when new materials are used and the fabrication costs are increased accordingly. Thus, unless the stabilizers of the temporary type shown in Figs. 4 and 5 can withstand a major flood, the agencies concerned stand to lose a large investment in both time and money in addition to the loss associated with the failure of the fences and groins dependent upon the stabilizer for stability.

4. Treatment of the Banks

By sloping the banks and by encouraging the growth of vegetation on them as an erosion deterrent is generally considered highly desirable. When possible, the banks are sloped to their natural angle of repose, and vegetation in the form of grasses, brush and trees is planted on them.

When a channel is deeply entrenched with nearly vertical banks, such sloping is not usually possible due to the large width required. Instead, the frequent caving of such banks is tolerated in the hope that the channel can be made to fill by the use of grade stabilizers to a height where bank sloping and treatment is possible.

Frequently, the lack of proper water supply makes the cultivation of vegetation impractical. In some dry areas drought-resistant plants have been used with success. Some of these grasses and brushes tend to spread into adjoining fields and residential areas where they consti-



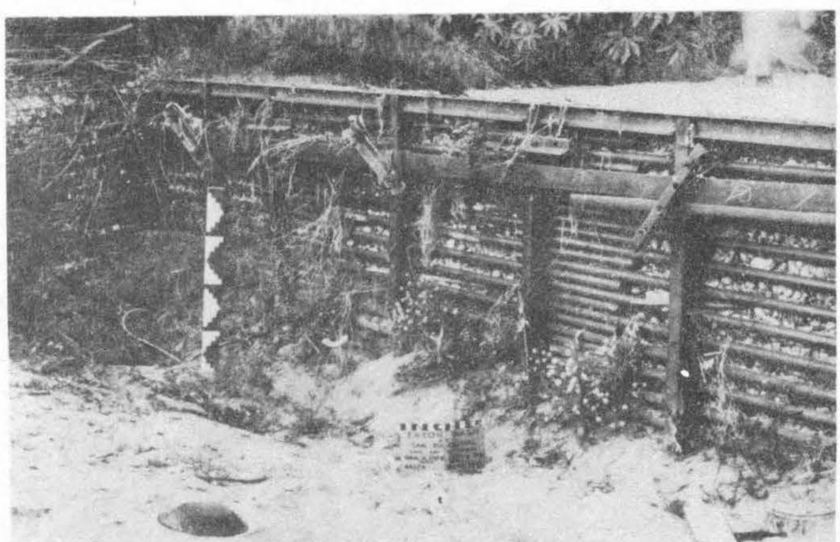


Fig. 5 - ROCK CRIB AND PIPE AND RAIL GRADE STABILIZERS

(a) Looking upstream at a rock crib stabilizer. Note stilling basin with transverse sill. (b) Looking upstream at rail and pipe stabilizer. Improvised stilling basin of mortared rock is buried under sand.

tute a nuisance, and for this reason they cannot be used as bank vegetation. In cases such as these, brush is frequently placed at the toe of the sloping bank and behind the fence and the bare banks above are accepted.

5. Maintenance

Maintenance is generally covered by directives which state that the revetted channels shall be inspected at definite intervals during the dry periods and those of intermittent flow and that continuous inspection of certain reaches shall be made during floods. Standby repair crews are provided to make emergency repairs such as bracing a section of fence that is being undercut, and reinforcing with a rock fill a portion of bank which has been scoured. From the inspections, maintenance programs are prepared. Items on this program may include: the replacement of fences overturned or undercut, the backfilling of groins and stabilizers, the addition of extra fencing to sections that have been damaged by the flood or that have deteriorated, the replacement of brush between fences.

The fences and grade stabilizers constructed of pipe, and rail with wire fencing do not seem to rust enough to make this problem a major part of the maintenance program in Southern California except near the ocean. Such might not be the situation in other climates in which case rust resistant construction materials may have to be used.

D. Behavior of Field Installations

Many of the earlier fence revetments in Southern California were built in streams which originally carried a heavy sediment load, most of which was picked up in steep mountain gorges and spilled into the valleys below. Through the years debris dams were built in the mountains to catch part of this load to reduce the flood hazards in the valleys. Therefore, the flow into the channels below the dams was usually deficient in sediment and the channel beds were scoured to relieve this deficiency. In some cases this action was so violent that artificial controls which stabilized the channel grade were undermined and/or cut around and the fences upstream were undercut and failed as shown in Fig. 6. Distortion of the bed by sand waves produced local scour that

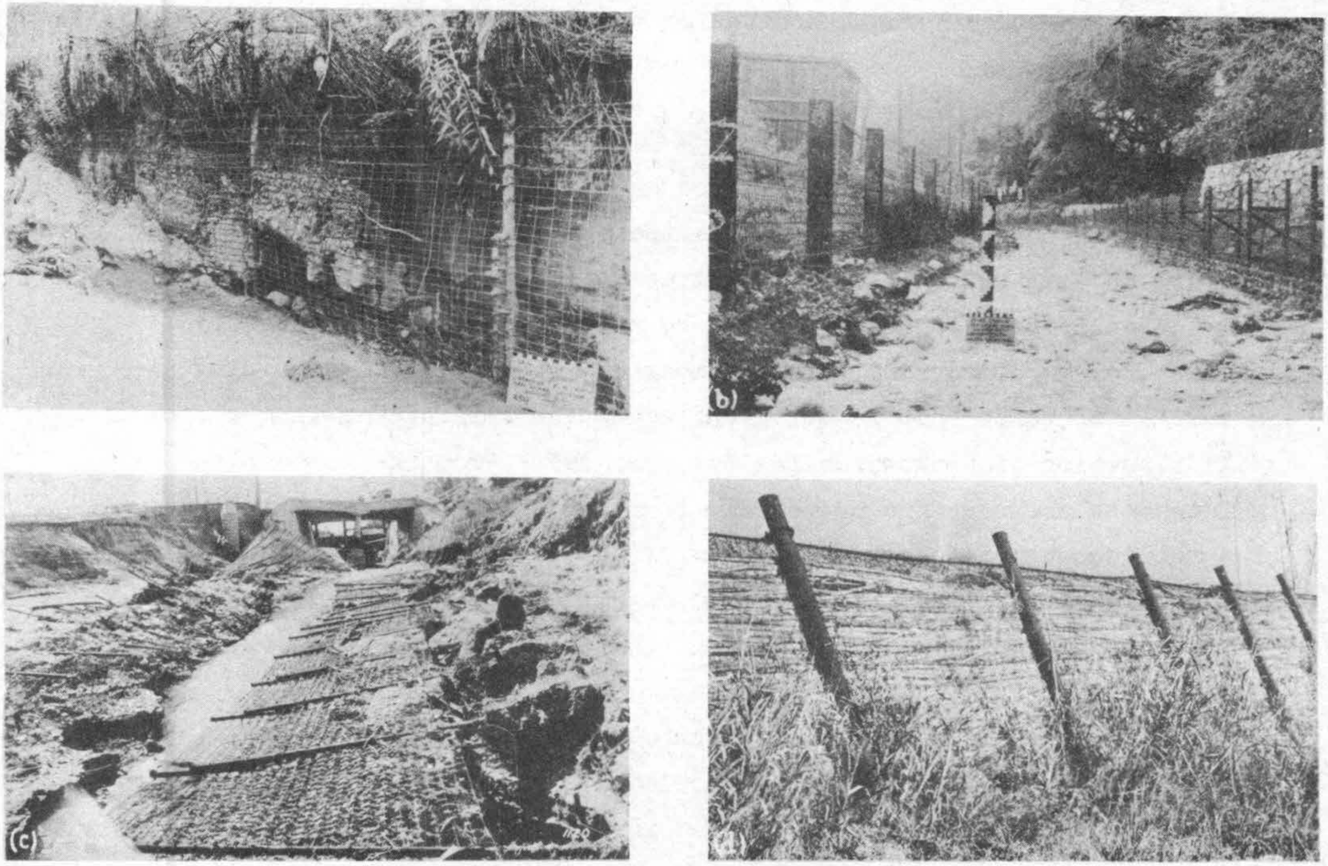


Fig. 6 - PIPE AND WIRE AND TIMBER AND WIRE FENCES AFTER FLOWS

(a) Severely undercut pipe and wire fence repaired by driving second row of pipes and adding new fencing. (b) Looking upstream at timber and wire and pipe and wire fences in same channel. Note horizontal fencing along right bank. Should the channel bed be eroded this fencing would swing downwards toward the vertical to help protect bank. (c) Pipe and wire fence which failed due to undercutting and lack of lateral braces. Looking downstream at broken control point. (d) Pipe and wire fence set purposely along sloping channel bank. Looking upstream at outside of curve. This fence survived a flood of 1500 cfs which topped it by 1 ft (see Bradley reference). Pipe is 2 7/8 in. in diameter, 14 ft long driven 8 ft into the bed at 1 on 1/2 slope and held in place by a dead man at each pipe.

caused many fences which were not driven deep enough into the bed to be tilted and in some cases toppled.

The funds available were often inadequate to construct grade controls which were structurally and hydraulically stable; therefore improvisations were built using pipes, rails, timber cribs and the like. The early attempts resulted in many failures due principally to piping through and around the stabilizers and to undermining at the base by local scour and by the general lowering of the unstabilized grade below the control. Many of these stabilizers were left after a flood in the center of a greatly widened section of stream. These failures were met by repairs and revisions which improved many installations and made them capable of weathering other floods without prohibitive damage. Small flows over two such structures are shown in Fig. 7.

Occasionally the installation of check dams to reduce downcutting produced filling in the channel which buried the fences and dams to depths feasible for study only by an archeological expedition well-equipped for digging.

Even in the tangent section of the streams it was early noted that notwithstanding stable pervious fence revetments, the flow tended to erode the banks and to cause a progressive widening of the stream in the direction of flow. To reduce this widening, groins or backlegs were constructed in the bank generally at an angle of 45° with the flow and pointing downstream. The sides of the groins were vertical, the toe was at the toe of the bank and the top was horizontal at an elevation usually near the level of the design flow. Since these represented flow obstructions similar to the grade stabilizers the erosion effects observed were similar. The water was accelerated immediately downstream from the groins producing concentrated scour of the bank and the bed that caused the groin to be undercut and frequently to topple as illustrated in Fig. 8. Eddying upstream from the groin caused scour there and tended to cut between the groin and the bank. However, when well anchored into the bed and banks, the groins proved a highly satisfactory bank revetment in themselves and greatly aided the fence when used with it.

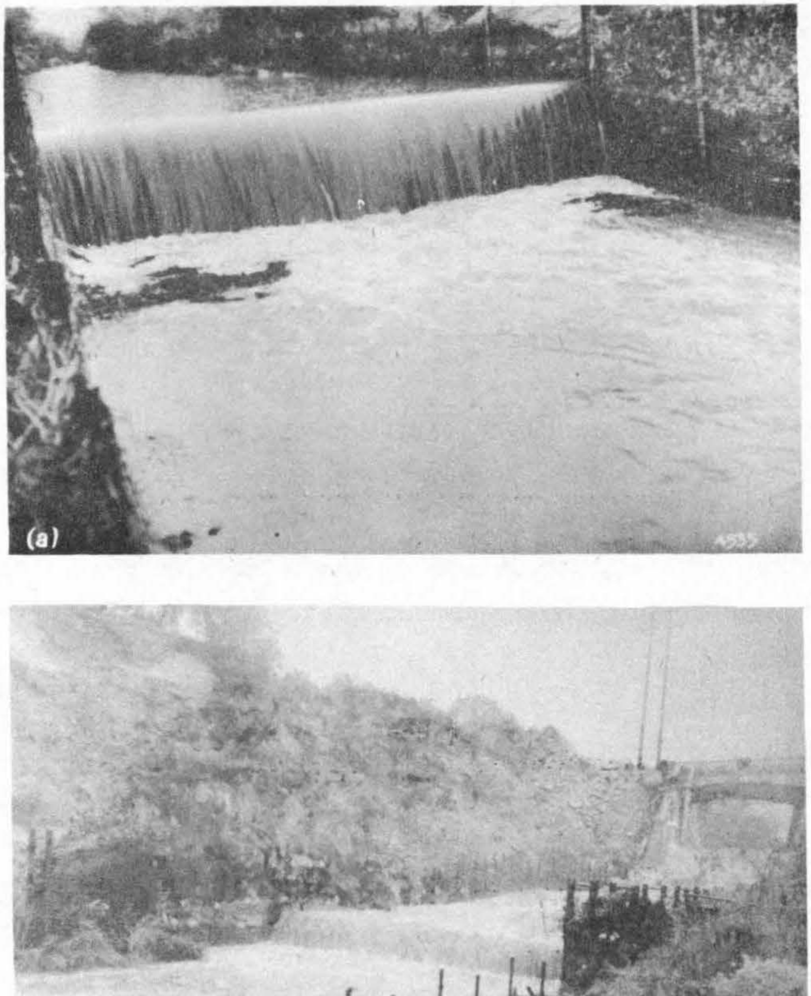


Fig. 7 - FLOW OVER GRADE STABILIZERS

(a) Sheet steel stabilizer. Discharge is about 100 cfs. Width 30 ft and depth at crest about 2 ft. A brush mat is used to form a stilling basin. (b) Pipe and rail stabilizer. Discharge is about 150 cfs. Width 35 ft and depth at crest about 1 1/2 ft. Note partially brushed double fences.

Fig. 8 - GROIN WHICH FAILED

Looking upstream, the flow over and around the groin was sufficient to undermine its supports and cause it to topple downstream.

Most of the streams considered carry, besides their sediment load, large quantities of suspended debris such as tree twigs, leaves, grasses, and the like, part of which gradually attaches itself to any suitable obstruction of the stream. The fence offers a very acceptable place for debris to cling to, after which the suspended sediment deposits around it and helps to mold the leafy tufts and the like into a substance with tough cohesive properties. When attached to the fence such small debris serve principally to dampen the transverse waves which are generated in the main stream and continually lap at the stream banks. The quantity of such debris seems to be greater during the rising stages than during the falling since the potential supply from the contributing watershed is greater during the rising stages. While flows were being observed in the field the debris was actually removed from a part of a fence. This area was recovered in a short time. The fence with such attachments forms a flexible wall that is much more effective in protecting the banks than the fence alone. Figure 9 shows a rail and wire fence in a debris-laden channel along with the flow action upstream from a groin.

When debris lodges on the fence it becomes less pervious thereby and is subject to increased overturning forces. In addition, the fence was observed to serve as a guide wall for the larger debris and to keep it floating toward the main thread of the stream where there was less likelihood that it would plug the channel and cause filling. The fence was subject to considerable overturning moment produced by the debris striking it.

The earlier fences were not braced laterally nor were the double fences tied together to enable them to operate as a unit; consequently they were often overturned. Many of these double fences were overturned also because the brush placed between them to increase their effectiveness had been piled so high that the fence was unable to resist the net pressure of the water against it. The fences proved more stable when lateral braces were installed and the brush carried to only about one-half the full height.

It is, of course, possible to carry the brush in a double fence to the full height and in other ways reduce the perviousness provided

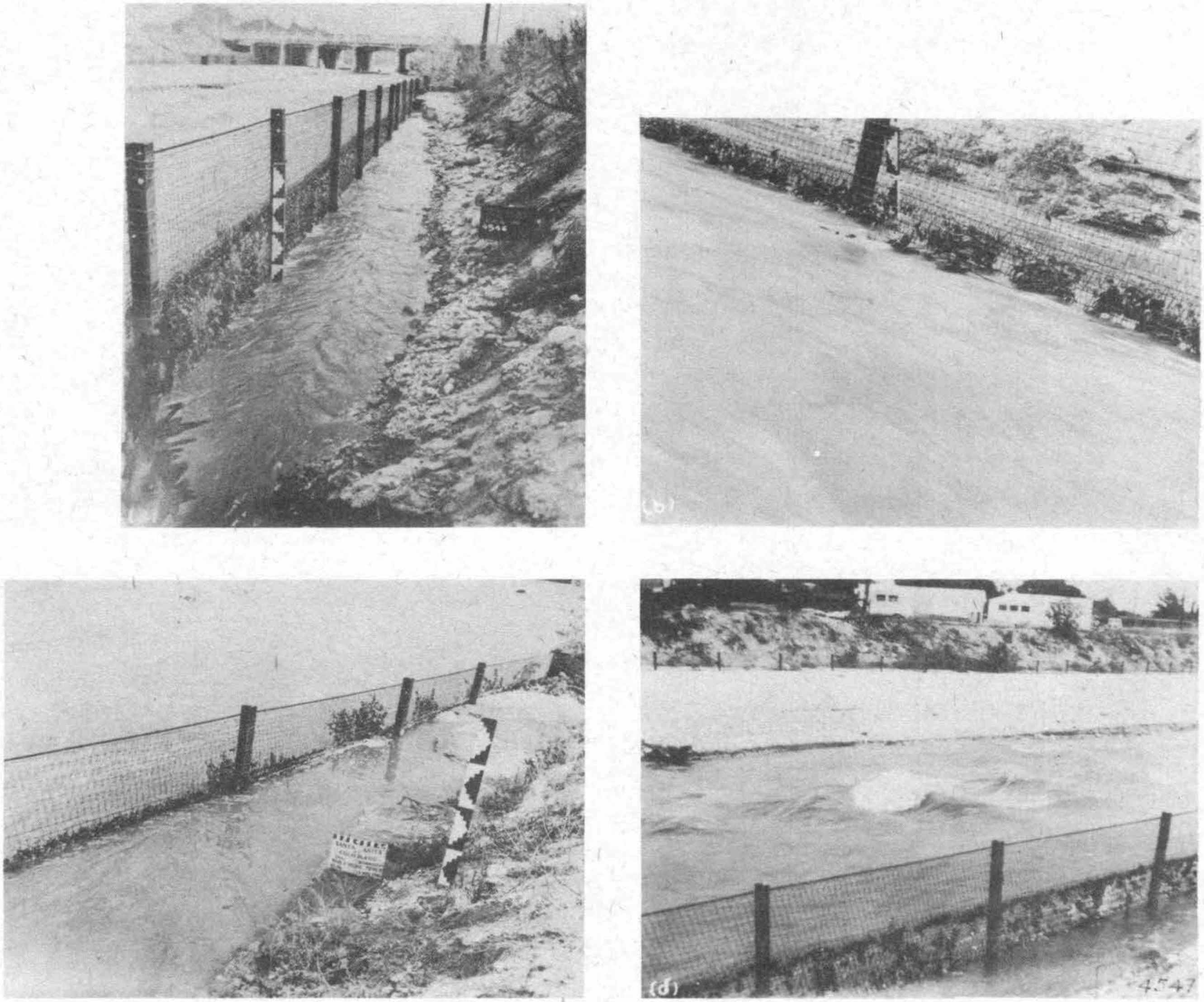


Fig. 9 - FLOW AROUND FENCE AND GROINS

Discharge is 100-300 cfs. All views looking downstream. Fence is rail and wire. (a) Note debris and sediment deposit upstream from groin in center background. Note waves off fence and banks. Depth is about 1/2 ft at fence. Sand waves are forming in channel. (b) Flow right to left. Note debris on fence. (c) Note standing waves off fence and pool upstream from groin. (d) Flow is left to right. Note sand waves breaking upstream in channel and debris on fence.

the fence is made stable against particularly the dynamic forces of the flowing water. The effect of considerable flow on such a well-designed fence is presented in Fig. 10. Here the fence, located on the outside of a curve as a training wall, was brushed nearly to its full height of about 6 ft. but was so constructed that it was able to turn the flow which overtopped it by about 2 ft. with but very small damage to the fence and the bank behind it. Note in Fig. 10 how the debris from the flood has attached itself to the fence, particularly that portion of the background.

Debris, when closely packed in the fence as shown in Fig. 10, gives the fence an appearance of semi-imperviousness as in some of the fences inspected in Orange (California) County. Here, as shown in Fig. 6-d, the pipes are driven at a 1 on 1/2 slope toward the banks. The fencing is fastened on the bank side of the pipes and backed by closely-packed native reeds. The soil is backfilled against the reeds to form with its opposite a bank-lined trapezoidal cross section. As observed and reported by Bradley (6), such a fence was able to withstand a large flood without serious damage. However, fences of this type were not the particular concern of this investigation.

The newer installations, especially in Los Angeles County, have fences continuous along the toe of both banks. Single fences are used in the tangent sections of the stream and along the inside of curves, while double fences are used along the outside of curves. However, many installations use double fences along both banks. Structural stability is considered more carefully so that the fence members are driven deeper into the channel bed and bank and are spaced closer together and the vertical members are braced laterally with more care.

It appears important that wherever possible, brush be used between double fences or between single fences and the bank. Old tin cans are sometimes used between double fences. The filling seems to be particularly necessary for the fences along the outside of curves and for those at the approaches to and exits from the grade stabilizers.

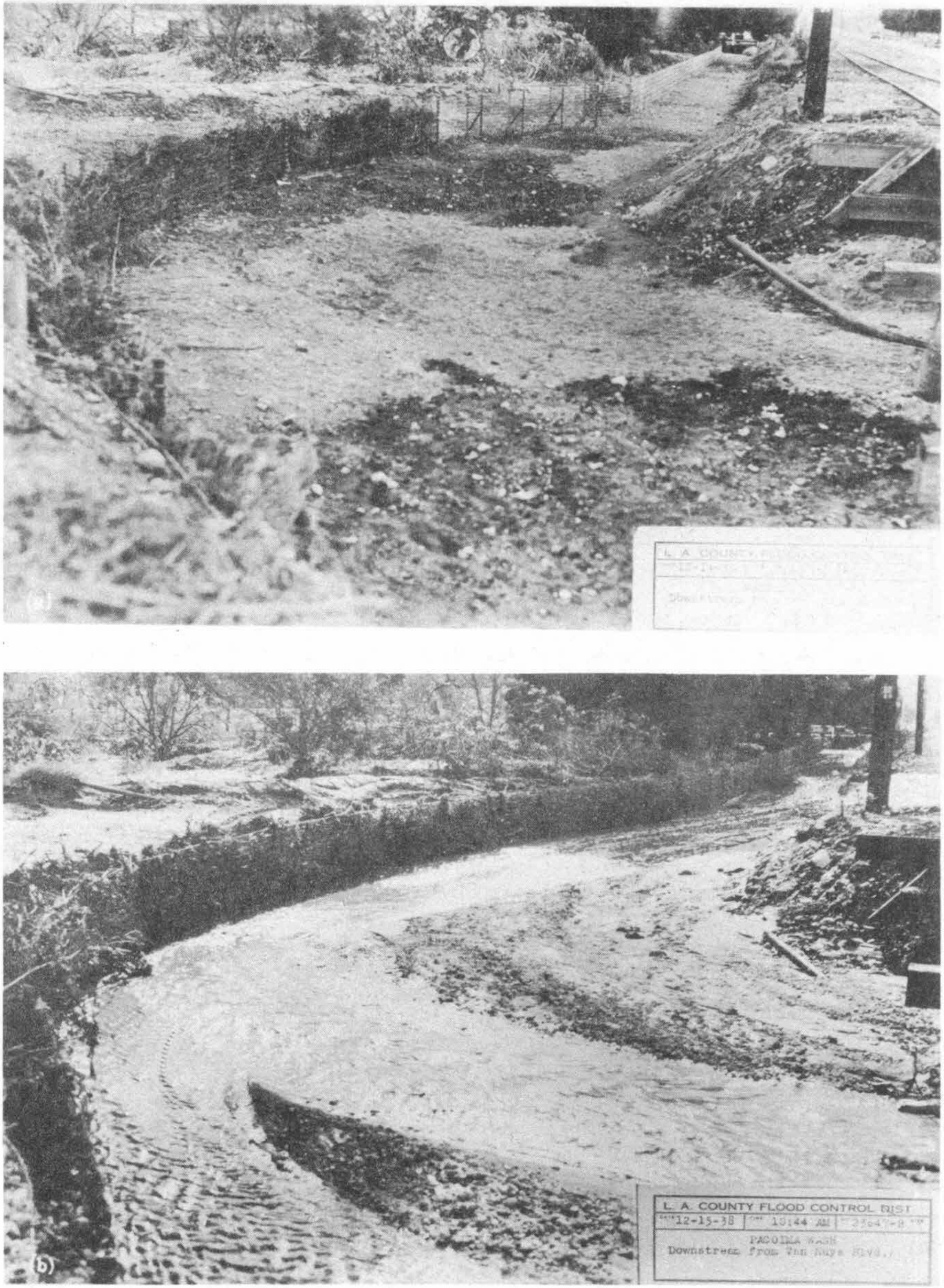


Fig. 10 - PIPE AND WIRE FENCE BEFORE AND AFTER FLOOD

Looking downstream at fully brushed and braced double pipe and wire fence. (a) Before flood. Fence is about 6 ft high. (b) After flood which overtopped fence by 2 ft. Damage was very slight.

IV. LABORATORY STUDIES

A. Introduction

The laboratory experiments were divided into two groups, I and II, which differed only in that the test channel was made longer in the latter case and a wooden instead of a sand terminus used therewith. The channels were constructed of the same sand, to the same cross section and slope, and the approach conditions were kept the same. The details for both of the channels are given in the following section.

B. Apparatus

A concrete basin 2 ft. deep, 10 ft. wide and 70 ft. long of rectangular cross section as shown in Fig. 11 was used for the study. The water supply system available was capable of continuously circulating sediment-laden water by means of an irrigation type propeller pump, which drew from a sump and discharged into a 10" dia. pipe. The pipe contained a Venturi meter to which a manometer was attached for the measurement of the discharge. The flow entered the upstream end of the concrete basin vertically upwards through the 10" dia. pipe, from where it flowed through the test channel to the pump sump at the downstream end.

For the experiment being discussed a rectangular wooden flume 2 1/2 ft. wide, 1 1/2 ft. deep and 32 ft. long was installed at the discharge end of the 10" pipe and extended downstream to a connection with the study channel. This channel was composed entirely of sand and was trapezoidal in cross section with a 2 1/2 ft. wide bed and sides sloped 1 on 2 1/2 to a height of .38 ft. as shown in Fig. 12. Its length was 16 and 32 ft. respectively for the Group I and II experiments while the bed slope was .0104 in both cases.

For the Group I experiments the test channel terminus was made of sand and served as an abrupt transition into a sand discharge channel about 5 ft. wide 16 ft. long with 1 on 2 1/2 side slopes which channel terminated at the pump sump. For the Group II experiments the terminus was made of wood 3/4" thick shaped to the channel cross section. The discharge from the terminus was directly into the pump sump.

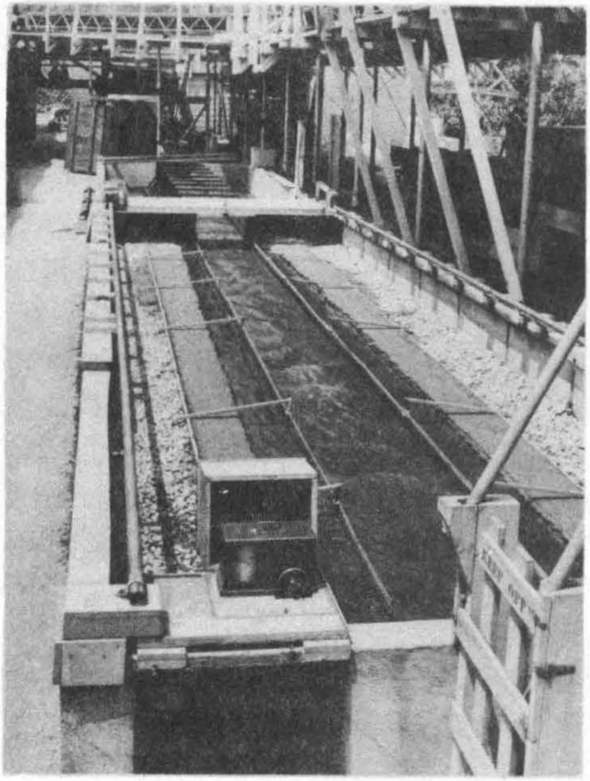


Fig. 11 - CHANNEL AND APPARATUS USED FOR LABORATORY TESTS

Looking upstream at 2 1/2 ft wide channel in which flow is 1 cfs. Observer in rear background is sampling the suspended sand load. A point gage is shown attached to the downstream end of the wooden approach flume and the manometer used with the Venturi meter is housed in the long narrow vertical shelter to the right of it. The water level recorder used in the pump sump is shown in the middle foreground.

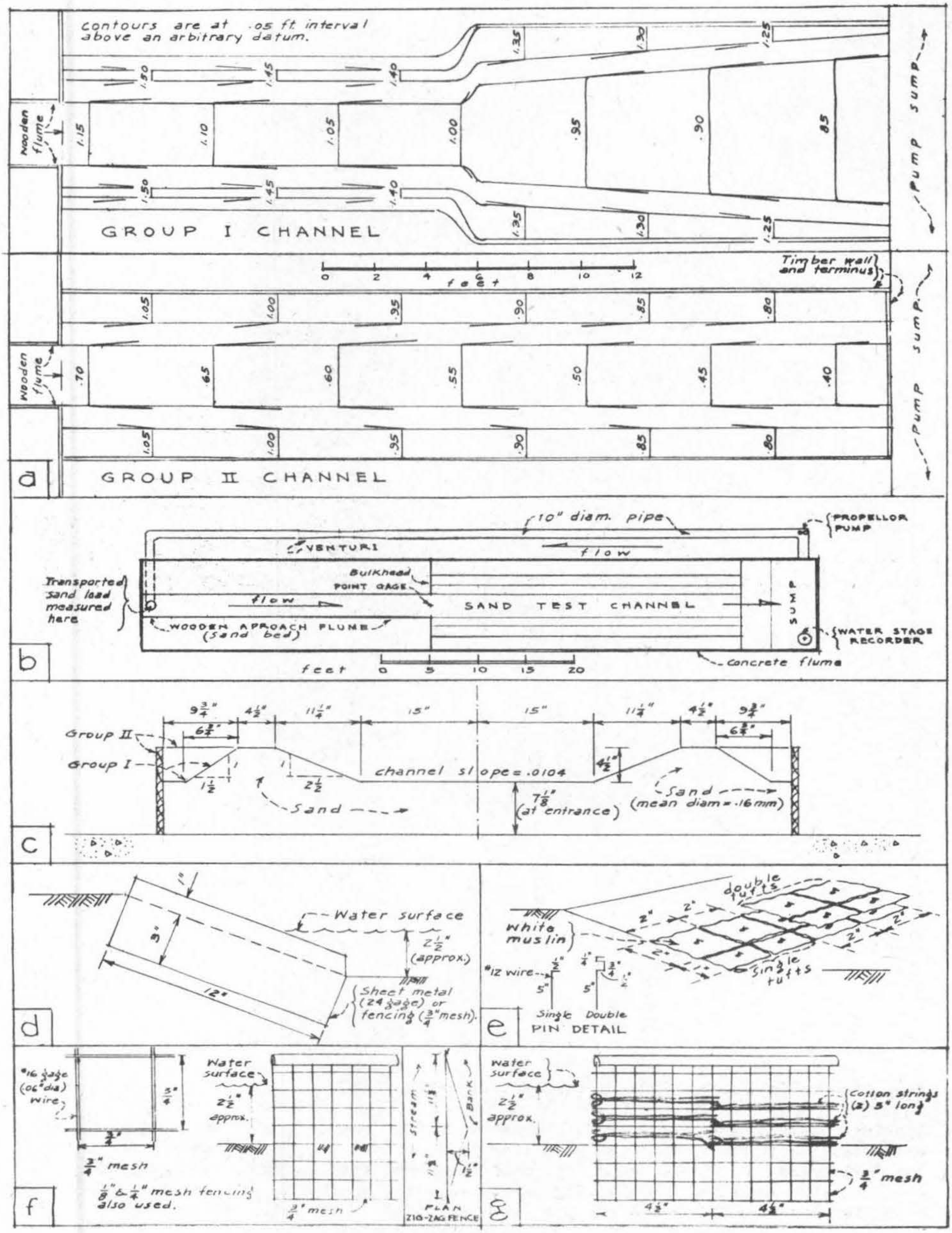


Fig. 12 - DETAILS OF LABORATORY TEST CHANNELS AND REVETMENTS USED THEREIN

(a) Group I and II channels before runs. (b) Schematic of circulation system. (c) Cross section through test channel. (d) Groin details and layout. (e) Tuft details and layout. (f) Fence details. (g) Debris layout.

The study channel banks as shown in Fig. 12-c were .38 ft. wide at the top with a 1 on 1 1/2 back slope for the Group I tests, while with the Group II tests the banks were 1.2 ft. wide at the top and were terminated by a board 3/4" thick set vertically and parallel to the centerline of the channel. Sand with a mean diameter of .16 mm was used for the construction of the test channel and in the bottom of the approach flume.

Besides the Venturi meter with which the total discharge was measured, instruments used included: a graduated flash for the volumetric measurement of the sediment in the flow, a point gage for measurement of the water level at the upstream end of the sand channel, and an automatic water level recorder which gave a continuous record of the tailwater level at the pump sump. The location of most of these is indicated in Fig. 11. Cork floats were used to obtain surface velocities and a graduated rod with a foot was used to obtain water depths.

C. Procedure

Preliminary runs were made in the sand test channel to determine an approximate equilibrium slope for the bottom. These runs indicated that with an unrevetted channel a slope of .010 was likely. Consequently, this slope was used in the construction of alltest channels. Before each run the channel was constructed to the standard dimensions (see Fig. 12) with damp sand, using a template of proper cross-sectior as guide. The two ends of the template rested on properly sloped side rails for the Group II experiments and its setting was checked by an overhead adjustable pointer in the Group I experiments so that the slope of .010 was maintained in all constructions. A movable platform suspended above the channel and independent of it was used in this work.

After the channel was built, the bank revetment to be tested was put in place and the still water level was brought to a predetermined tailwater elevation to insure the proper quantity of water in the system. This quantity was not altered during the experiment.

The flow in the closed system was started in circulation from rest by abruptly starting the pump at the setting for 1 cfs discharge. A short time was, of course, necessary for the flow to attain this rate throughout the whole system, during which there was some scouring and filling.

The procedure during any particular run was to maintain the discharge at 1 cfs (as measured at the Venturi meter) until the banks of the channel had eroded an amount kept as a standard; namely, until the dikes of the Group I channel had been breached at any point or until the dikes of the Group II channel had widened (breached) 25 1/2 inches (see Fig. 12-c) from the original toe of the banks at any point. The elapsed time from the start of the run to breaching was recorded, and was the basic criterion for performance of the sand channel with or without bank revetment.

When breaching occurred, the run was terminated by abruptly stopping the pump and allowing the flow to come to rest. The channel scour pattern was contoured by placing white woolen strings at certain even elevations (contour intervals of .05 ft.) throughout the pattern. The elevations were delineated by the water line of the still water surface which was carefully adjusted until proper, as determined by readings of the tailwater recorder. The resulting contoured relief map was recorded by a plan photograph. After this the test channel was rebuilt from material which had been deposited in the bed of the old channel and downstream therefrom.

Duplicate runs were made with some revetments to check the experimental techniques but generally each revetment was tested only once.

During the runs visual observations were made using dyes and confetti, and plan and oblique photographs were taken to record particular flows and each scour pattern.

The sediment load was checked frequently from samples taken with a graduated flash at the pipe exit at the upstream end of the wooden approach flume. The sample taken was allowed to stand until the water and sand in the mixture had separated, after which the volume of the mixture and sand were read and recorded. The concentration of sand in the flow in percent by weight was calculated using the relation: sand load in percent = $\frac{\text{volume of sand} \times 1.6 \times 100}{\text{volume of sand and water}}$ on the basis that the specific gravity of wet sand is 1.6.

Measurements of the slope of the moving water surface were made using a stationary point gage located at the upstream end of the test channel together with a float type water level recorder located at the downstream end, both as shown in Fig. 11. Simultaneous readings repeated many times were taken on the water surface with these two instruments, and the results were properly reduced and averaged to give the average slope. The results were complicated by the very wavy water surface and also by the fact that only two measuring locations were available. However, since an average of a large number of readings was used, it is felt that the values obtained are indicative of at least the slope of the water surface between the two extremes of the channel.

D. Performance of Various Revetments

1. Introduction

A composite of the results of the tests in the sand channel are presented in Table I. The results are separated into those for Group I and II tests since the channel lengths were respectively 16 ft. and 32 ft. and the terminal conditions were slightly different as given in section IV-B and shown in Fig. 12, although the initial cross sections and bed slopes were identical.

As a means of comparison the term "effectiveness ratio," as abbreviated to "ER," is used in this report. The ER of a particular revetment is defined as the ratio of the time necessary to breach the channel banks when protected by this revetment to the time necessary to breach the unrevetted or bare banks. Thus an increase in the effectiveness ratio (ER) means an increase in the protection given the banks against breaching or this increase in ER may be interpreted as a decrease in the rate of bank erosion.

The behavior of the Group I and II channels under the same discharge (1 cfs) in the unrevetted channel was slightly different, as a review of the time to breaching for the two runs (runs 12 and 34) given in Table I will show. However, by use of the effectiveness ratio, overall qualitative comparisons may be made with sufficient accuracy without qualifying either group.

The term "bank revetment" is used generally in referring to any structure used to protect the bank and includes the fence in front of

TABLE I

RELATIVE EFFECTIVENESS OF VARIOUS REVETMENTS TESTED

The fence referred to extended well above the water line and had fencing of 3/4" mesh unless noted otherwise. All revetments were placed symetrically along both banks of the test channel.

Condition of the Channel banks	GROUP I TESTS					GROUP II TESTS				
	Run No.	Sand Load % ††	Slopes		Eff. Ratio †	Run No.	Sand Load %	Slopes		Eff. Ratio †
			Water surf.	Bed final				Water surf.	Bed final	
NO REVETMENT	5,12	6.0	---	.0032	1 *	34	3.9	.0073	.0015	1 **
SINGLE VERTICAL FENCE										
alone	4, 10,11	4.7	----	.0072	1.6	37,38	2.4	.0067	.0034	1.8
alone, ½ depth high						35	2.9	.0064	.0046	1.8
alone, 1/8" mesh						33	2.6	.0082	.0045	2.8
with debris attached						18	6.6	-----	.0135	2.5
						39	2.1	.0078	----	2.7
DOUBLE VERTICAL FENCE										
alone	9	5.3	----	.0077	2.9					
alone, zig-zag						21	4.0	----	.0058	1.8
with debris, fences of ¾" & ¼" mesh						19	6.7	----	.0114	4.2
REINFORCED BANKS ONLY, NO FENCE										
groins, solid										
90° at 2 ft. c to c	6	5.9	----	.0067	9.4					
45° at 2 ft. c to c	7	3.9	----	.0067	>13.5					
tufts, single										
100% bank covered						26	2.2	----	.0052	2.3
tufts, double										
100% bank covered						28	2.1	----	.0086	6.3
SINGLE FENCE AND REINFORCED BANKS										
groins, solid										
90° at 1 ft. c to c	1	4.5	----	----	>13.5					
90° at 2 ft. c to c	2	5.3	----	.0175	>13.5					
90° at 4 ft. c to c	3	5.3	----	.0121	12.3					
groins, mesh, 3/4"										
90° at 1 ft. c to c	8	4.4	----	.0094	4.6					
45° at 1 ft. c to c						20	3.0	.0078	.0104	4.7
tufts, single										
100% bank covered						23	1.6	.0065	.0071	5.7
50% bank covered						25	1.2	.0071	.0058	3.5
17% bank covered						24	1.5	.0069	.0065	2.1
tufts, double										
100% bank covered						32	2.7	.0070	.0074	>21.9
50% bank covered						27,36	1.5	.0070	.0074	8.0

* time to breaching was 1.6 hours

** time to breaching was 1.2 hours

† $\text{Effectiveness ratio} = \dfrac{\text{time to breach reveted bank}}{\text{time to breach unreveted bank}}$

†† $\text{Percent by weight} = \dfrac{\text{volume of transported sand}}{\text{volume of sand and water}} \times 1.6 \times 100$

the bank and the groins and cloth tufts actually in contact with the bank or any combination of these types.

It must be emphasized that the data presented represents only those collected from tests in a small sand channel which had no relation to any natural channel. The tests are not to be construed as a model study and the results cannot be directly extrapolated to natural channels. However, they may be interpreted as the qualitative comparison of the protection given the banks of the test channel by several different types of bank revetment, and on this basis they permit the various groups to be ranked **broadly** as to likely effectiveness in a straight section of an open channel with similar bed and banks.

2. General Characteristics of the Flow

The initial flow in the channel after a start from rest was in the form of a wave or bore as shown in Fig. 13, and since the water was relatively clean, the deposits of sand in the circulating pipe, approach flume, and sand test channel were scoured and their slopes altered until the flow gained its full rate of 1 cfs and the transported sand load rose to a constant value for any one revetment. As shown in Table I, the sand load varied between 4% and 6% by weight for Group I experiments and 1.2% to 4% by weight for the Group II experiments with two exceptions, runs 18 and 19 for the channel revetted respectively by a single and double fence with simulated debris (strings) attached to the fence in both cases, where the measured sand load was about 6.8%. Regarding these exceptions, it is difficult to understand how the sand load could increase so much over that for the unrevetted channel (3.9%) when the roughness of the banks was increased so much by the fence and debris. A decrease rather than an increase in the sand load would be indicated in this case. It will be noted in Table I that run no. 39 was made as a repeat of run no. 18 and that during this repeat run the sand concentration was measured as 2.1%. This is thought to be a reasonable concentration and is of the same magnitude as that for the other revetments. Therefore the concentration of 6.8% and 6.7% respectively for runs 18 and 19 are considered excessive, due possibly to inaccurate sampling and therefore they should be disregarded.

During the initial period, and periodically thereafter, a most spectacular flow characteristic was manifest. This was the cyclic growth and break-up of a train of waves formed on the surface by the flow of water along the channel bed distorted by bed load movement. These waves are referred to as "sand waves." A history of one such wave train is recorded in Fig. 13 which shows that the first symptoms were in the form of an undulated water surface which gradually steepened until a wave train with generally uniform spacing was visible. Measurements indicated that when the depth was about 0.2 ft. the maximum distance from the water surface to the crest of an undulation was about 0.4 ft. Since the distance between the crests was approximately 2 ft., the ratio of height to length was 1 to 5 which defines a very unstable water profile. These sharp peaks eventually toppled or "broke" upstream and the whole water surface was noticeably disturbed thereby in various directions. The cycle was then repeated. The initial mean velocity (V) was about 2 fps in water 0.2 ft. deep (d) which determines a Froude number ($F=V/\sqrt{gd}$) of about 0.8 and indicates that even in the early stages of the runs the flow was near the critical Froude number of 1. As the runs progressed and the channel continued to widen, surface velocities of 2 to 3 fps were measured with depths slightly less than .2 ft., so that the Froude number rose to greater than 1, that is the flow was supercritical. Such flow in itself produced a very disturbed water surface which was augmented to localized surge proportions by the periodic splashes from the breaking sand waves.

It was apparent during the tests that the forces acting against the banks of the channel were not limited to the classically conceived shearing forces but contained in addition the lateral components of the sharp surface disturbances described above. As observed, the most apparent attack on the banks was in the form of a never-ending lapping as on an ocean beach which progressively wore away the sloping bank up to an elevation equal to the maximum height of the surface disturbances. This inexorable lapping eventually undermined the bank in varying degrees until the cohesion of the sand, even when aided by mechanical stabilizers such as groins, could no longer support the increased surcharge which then caved into the channel. The banks did not

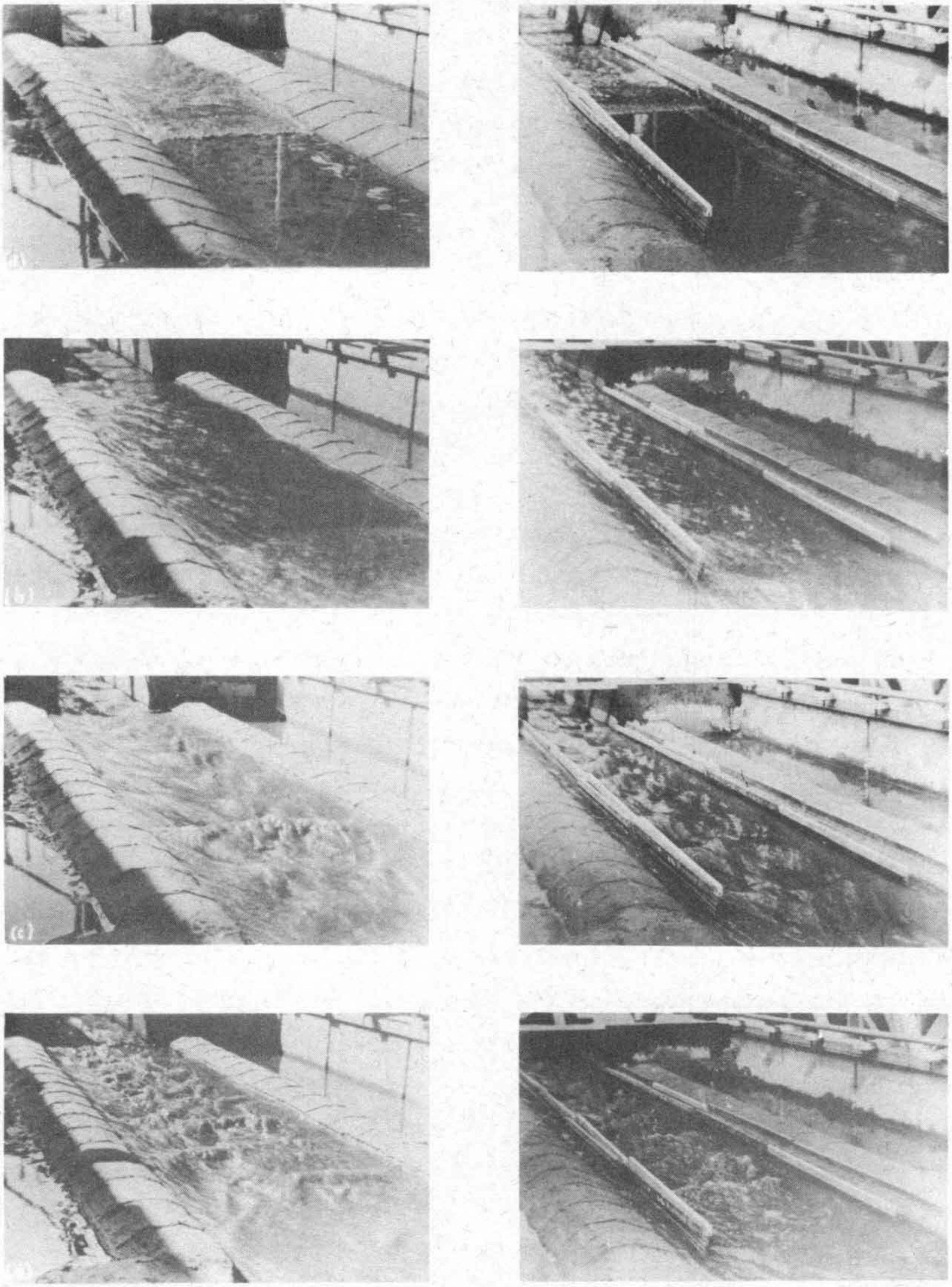


Fig. 13 - PICTORIAL HISTORY OF GROWTH AND BREAKUP OF SAND WAVES IN UNREVETED AND FENCE-REVETED TEST CHANNEL

The action in the unreveted channel and that with two 3/4" mesh fences are shown in parallel vertical columns. (a) Initial flow down channel after start from rest. (b) Surface begins to show undulations due to distortion of bed by sediment movement. (c) Undulations begin to form into wave trains. (d) Waves break upstream.

cave simultaneously along the full length of channel, for all parts of the banks were not eroded at exactly the same rate. The erosion pattern in plan was one of progressive widening of the channel in the direction of flow. The pattern with a fence revetment is shown in Fig. 14 and reflects the general erosion tendency of the channel when flow is occurring.

3. Fence

The fence alone, with fencing of usually 3/4 in. mesh, did not give at any time anything resembling complete bank protection, for with it there was always very obvious erosion of the channel. The presence of the fence, however, did reduce the rate of erosion, since with it the channel effectively contained the flow from 1.8 to 2.8 times longer than the unrevetted channel where the mesh of the fencing ranged from 3/4 inch to 1/8 inch. These values are taken from Table I.

As illustrated particularly in Fig. 15-a, the erosion forces consisted basically of two groups: first, those associated with the general current whose direction was downstream and parallel to or at a very small angle with the centerline of the channel. The direction and magnitude of this current is shown by the confetti streaks on the surface in Fig. 15-a. It is obvious that the surface velocities are lower behind the fence since the streaks are shorter there; however, the depths are less here than in the main channel. The second group of erosion forces were those associated with the wave disturbances whose direction was in many places at a very great angle with that of the main stream current. These disturbance waves are prominant in Fig. 15-a, both as sand waves in the main channel and as standing waves between the 1/8 inch mesh fencing and bank. Similar waves are noticeable in Fig. 16-a, although the main current, as with that in Fig. 15, is still directed downstream.

It is interesting to note in Table I the effect of doubling the 3/4 inch mesh fence. This was done in two ways: one, by placing two fences parallel and mutually touching along the toe of the bank, another by placing one fence in the usual position along the toe, and the second in a zig-zag pattern behind it such that they alternately touched and

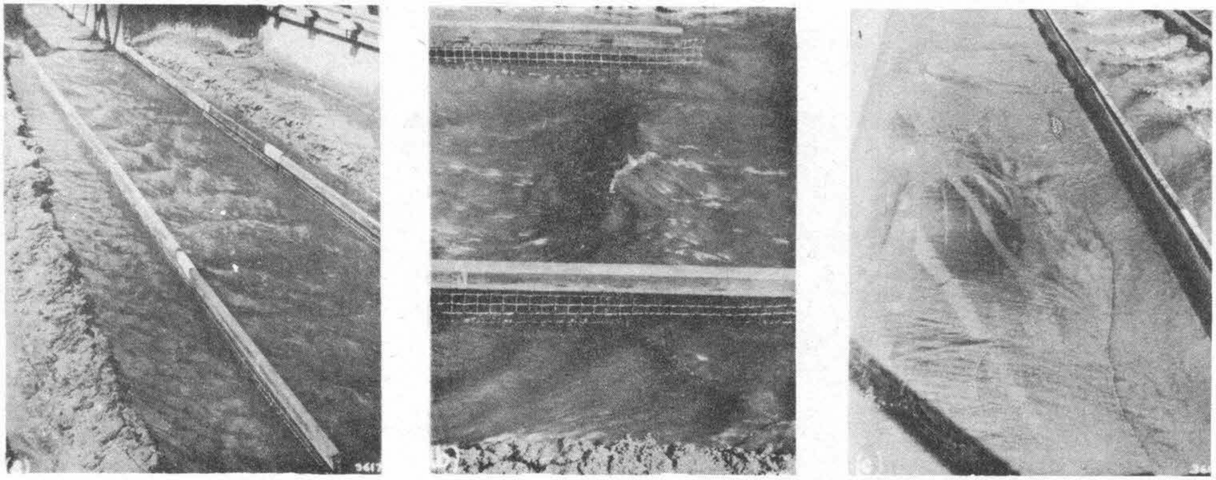


Fig. 14 - DISTURBANCES IN FENCE-REVETED CHANNEL

Fence is single 3/4" mesh. Channel is 2 1/2 ft wide and depth of water about 0.2 ft. (a) Looking upstream at severely damaged and widened channel. Note wave trains on surface and toppling sand banks. (b) Closeup of sand wave. Flow is from left to right. Wave is about to break upstream. (c) Looking downstream at channel with dikes completely leveled.

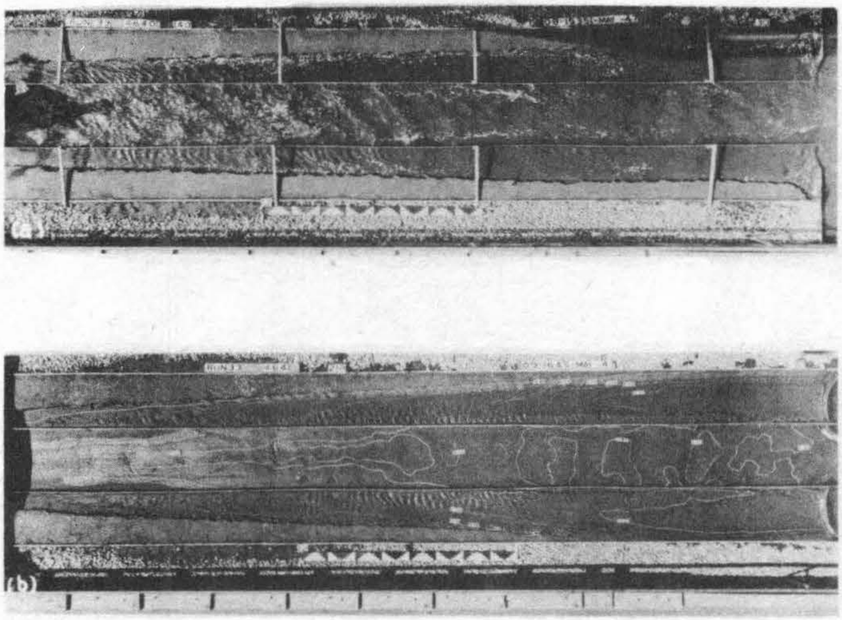


Fig. 15 - STREAK PHOTOGRAPH AND SCOUR PATTERN IN MESH FENCE-REVETED CHANNEL

Fencing is of 1/8" mesh. Run #33. (a) Streaks on surface are made by floating confetti during 1/50 second. Note slow speeds behind fence and standing waves off fence. Flow has been continuous for a time equivalent to an effectiveness ratio of 1.9. (b) Scour pattern after breaching. E.R. was 2.8. Note scour wrinkles coincident with standing waves off fence as shown in (a) above. Contour interval is 0.05 ft.

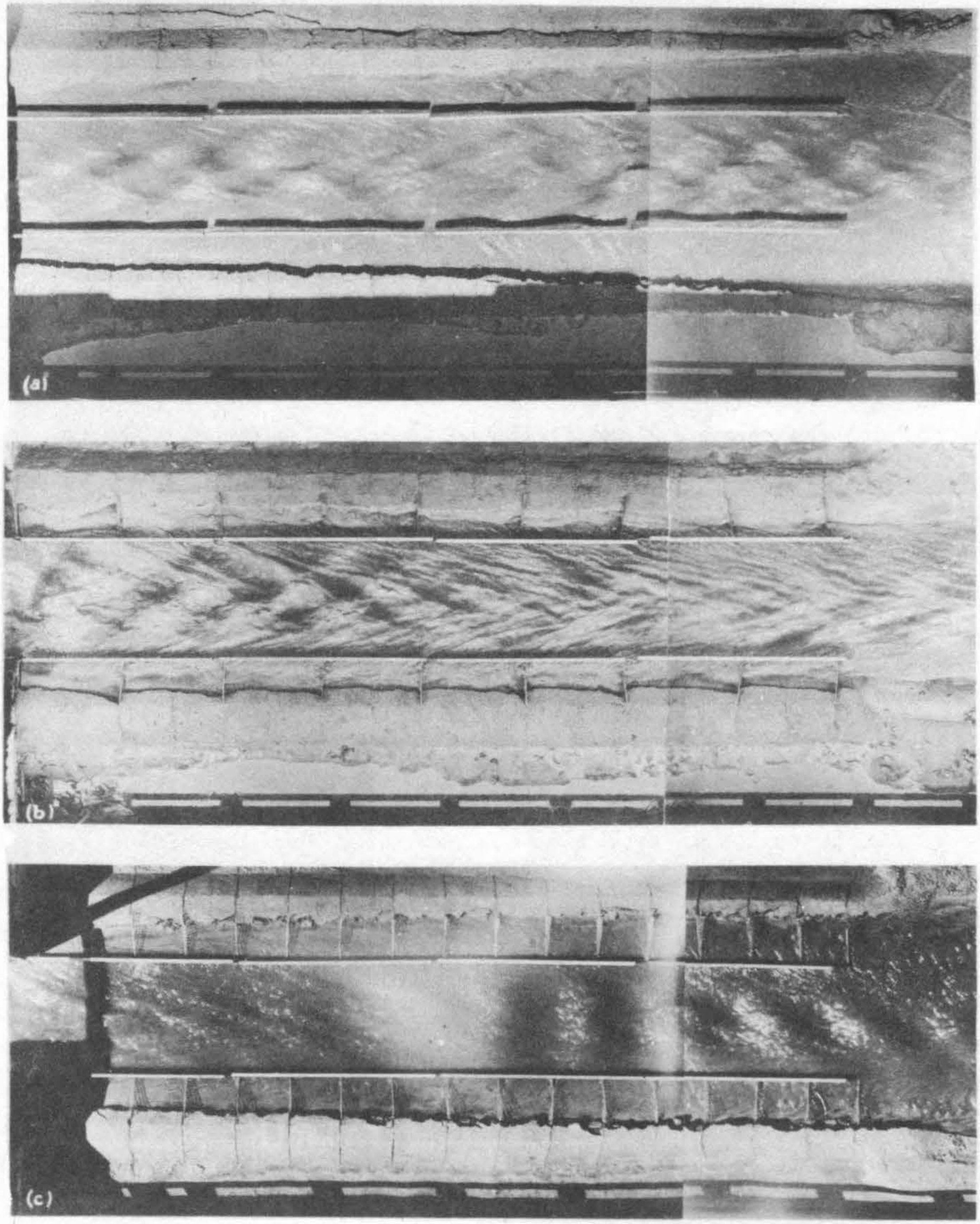


Fig. 16 - COMPARISON OF FLOW PATTERNS IN FENCE REVETED CHANNEL WITH AND WITHOUT SOLID AND MESH GROINS

Fence and mesh groins are 3/4" mesh. Flow has been continuous for a time equivalent to an effectiveness ratio of about 1.2 in all cases. (a) Fence alone. Note divergent pattern of widening and shear banks. Run #4. (b) Fence with solid groins set normal to the flow at 2 ft spacing. Note standing waves off the ends of groins and eddies around groins. Note scalloped banks in contrast to those in (a), Run #2, above. (c) Fence with mesh groins set normal to the flow at 1 ft spacing. Note divergent scour pattern similar to that with fence above and shear banks. Localized eddying not apparent. Run #8.

were separated by .125 ft. every .98 ft. as sketched in Fig. 12. The effectiveness of a single fence was increased by better than 1 1/2 times (from an ER of 1.7 to 2.9) by adding a second parallel to and touching the first but the zig-zag arrangement for the two fences was no more effective than the single fence alone.

The scour pattern developed with a single fence is shown in Fig. 17-a and is typical of that developed with the double fence also. Although marked widening of the channel occurred, the depth of scour was always less behind the fence than in the main channel. Reference to Fig. 12 will show that the bed of the channel was lowered around .05 ft. and the channel slope flattened from .010 to about .007 as given in Table I for run no. 4.

A fence with 3/4 inch mesh and about one-half water depth in height (0.10 ft.) was tested, and as shown in Table I for run no 35, it proved about as effective as the full height fence. The scour pattern as presented in Fig. 18-b is very similar to that for the full height fence.

As a means of simulating debris, cotton strings 5 inches long were tied to the fence at one end, while the loose end was left free to move with the flow as shown in Fig. 12. During the run, these strings clung to and swung free from the fence at more or less periodic intervals corresponding to the lateral wave action. With them the effectiveness ratio of the fence rose from 1.7 to 2.7 at the expense of a considerable increase in the final slope of the channel bottom namely from .003 to .014. This slope of .014 was not materially changed when a 1/4 inch mesh fence was placed parallel to and touching the first fence (3/4 inch mesh) with strings simulating debris but the effectiveness ratio was increased from 2.7 to 4.2 thereby as shown in Table 1.

The scour pattern for the debris-laden fence is compared with that for the short fence in Fig. 18. As indicated above and as shown in Table I, the final bed slope with the debris-laden fence is over four times as much as with the fence alone. The transported sand load also increased from 2.4% to 6.8% by the addition of the string debris to the fence.

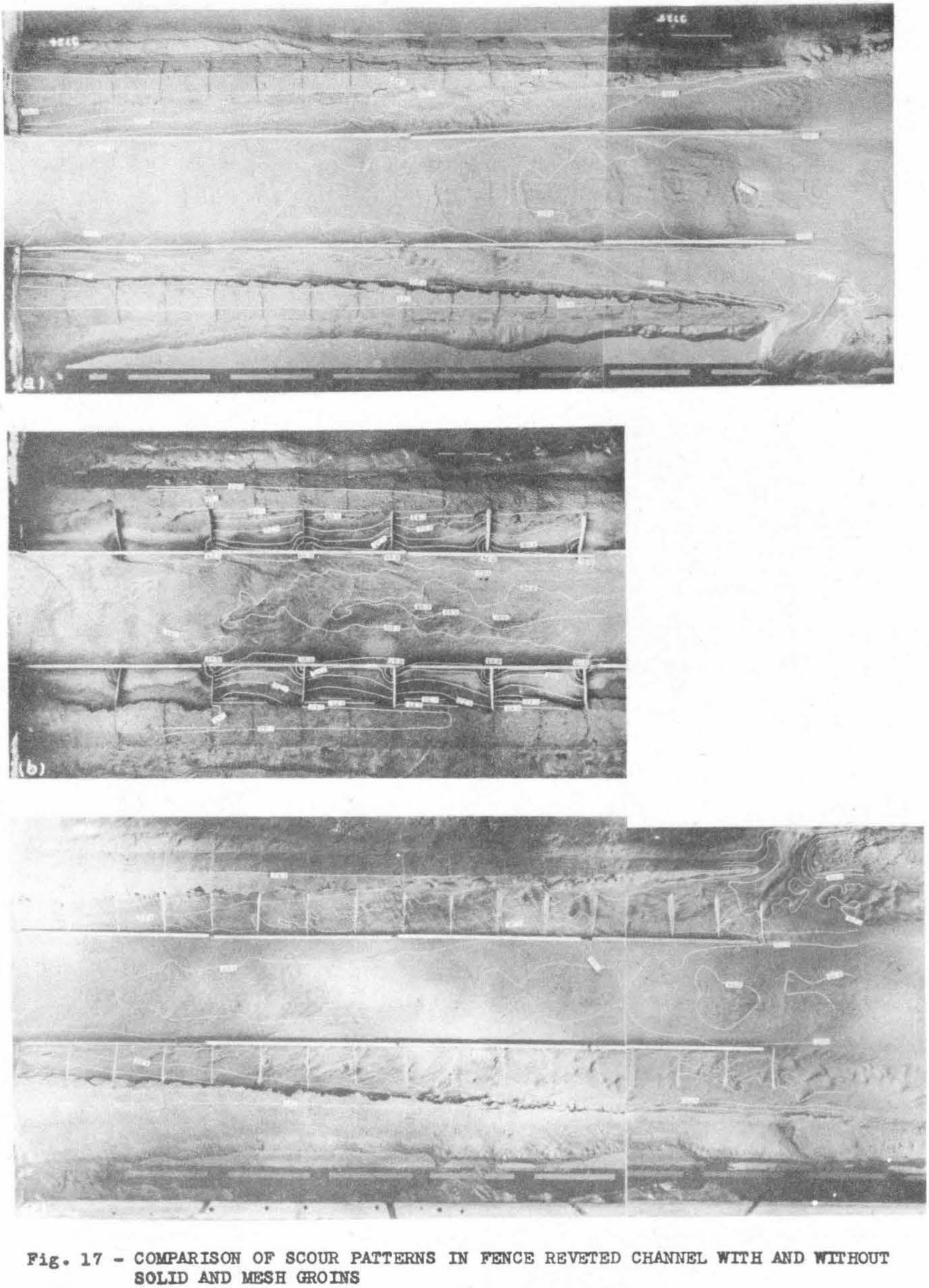


Fig. 17 - COMPARISON OF SCOUR PATTERNS IN FENCE REVETED CHANNEL WITH AND WITHOUT SOLID AND MESH GROINS

Fence and mesh groins are 3/4" mesh. (a) Fence alone E.R.= 1.6. Note divergent scour pattern. Run #4. (b) Fence with solid groins set normal to the flow at 2 ft spacing. E.R. = greater than 13.5 since run was terminated before breaching. Note scalloped banks and extent of local scour. Run #2. (c) Fence with mesh groins set normal to the flow at 1 ft spacing. E.R. = 4.6. Note divergent scour pattern and lack of appreciable local scour around groins. Run #8.

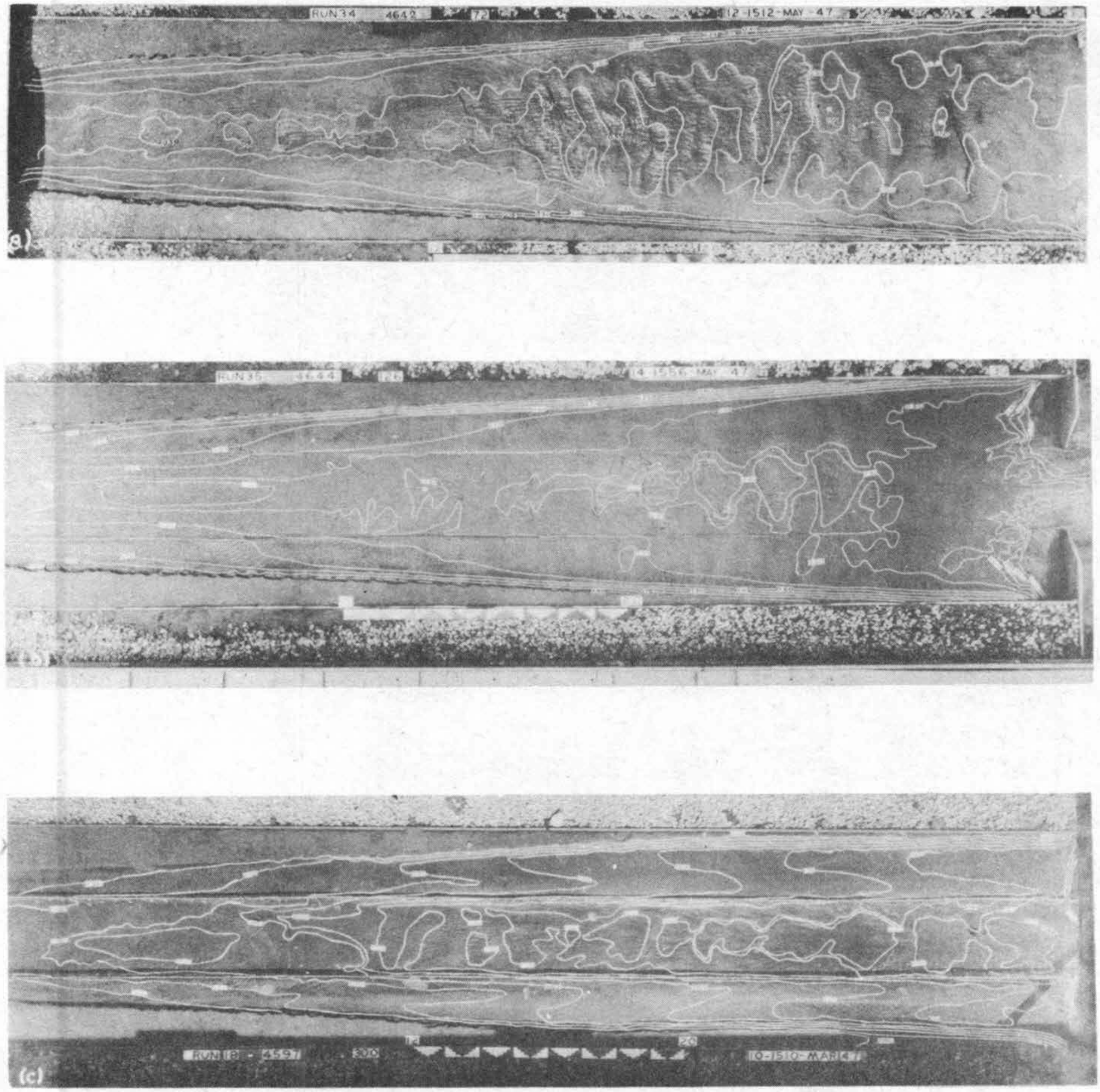


Fig. 18 - COMPARISON OF SCOUR PATTERNS IN UNREVETED CHANNEL AND THAT REVETED WITH SHORT FENCE AND REGULAR FENCE WITH DEBRIS ATTACHED

Fence in both cases is 3/4" mesh. (a) Unreveted channel. Run #34. (b) Short fence 1 1/4" high (1/2 depth). This divergent pattern does not differ from that with normal fence as shown in Fig. 25a. Note divergent pattern. Run #35. E.R.= 1.8 which is same as that for normal fence. (b) Full height fence with debris (strings) attached. E.R. = 2.7. Note that divergence of banks from station 15 downstream is very gradual. Run #18.

4. Reinforced Banks

In the experiments discussed in the preceding section the concern was with the evaluation of the protection provided by a vertical fence for the bare sand banks which were vulnerable to the wave disturbances created by the unsteady water surface once these had penetrated the fence. In the group of tests to be discussed here the concern was with the evaluation of the protection given the sand banks by groins and cloth tufts which were actually embedded in the banks, the latter to roughly simulate the effect of vegetation. These provided additional cohesion for the sand particles as well as shields for the exterior surface of the bank.

The cloth tufts (see sketch in Fig. 12) may be construed as simulated vegetation with the leaf-like cloth supported by a wire embedded in the bank similar to, but not nearly as extensively as, the roots of a shrub or tree. Although the tufts were made of fresh cotton cloth which fully covered the banks under them when dry, they gradually drooped about their wire spindle when soaked and as the bank was scoured from under them.

The tufts increased the ability of the banks to contain the flow as shown in Table I since the effectiveness ratio for the single and double tufts over 100% of the bank was 2.3 and 6.3 respectively. A plot of the effectiveness ratio versus percent of bank area covered by the tufts is presented in Fig. 19 based on the data contained in Table I. The advantage of bank covering is readily apparent from a study of this plot, but as shown in Fig. 20 the channel was considerably damaged, particularly widened throughout its full length even when the double tufts were used. Local scour was confined to a small area around the wire stem. The pattern with the double tufts is unique for the whole experiment; however, the rate of widening was greater in the center section than farther downstream as shown in Fig. 20. This is probably due to the large retardation exerted on the expanding flow by the double tufts. This matter is treated in more detail in section IV-E.

The groins gave more positive protection to the banks than any other single type of revetment tested. As may be seen in Table 1, the

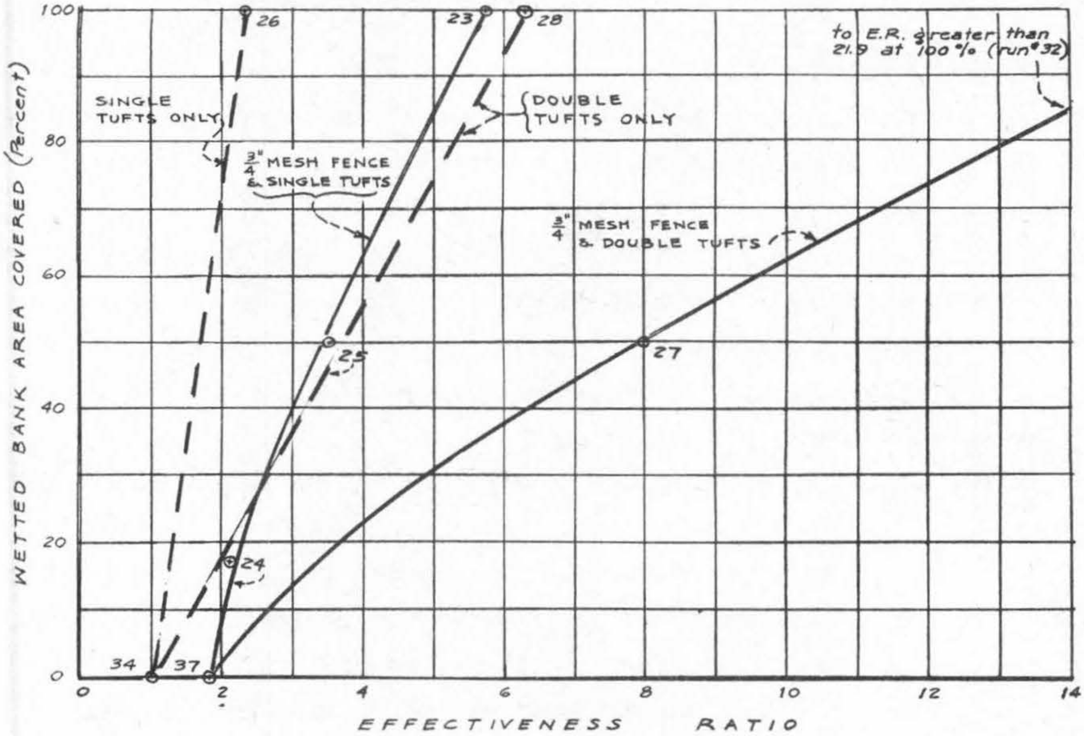


Fig. 19 - PLOT OF EFFECTIVENESS RATIO VERSUS PERCENT OF WETTED BANK AREA FOR CLOTH TUFT REVETMENTS.

Run numbers are shown.

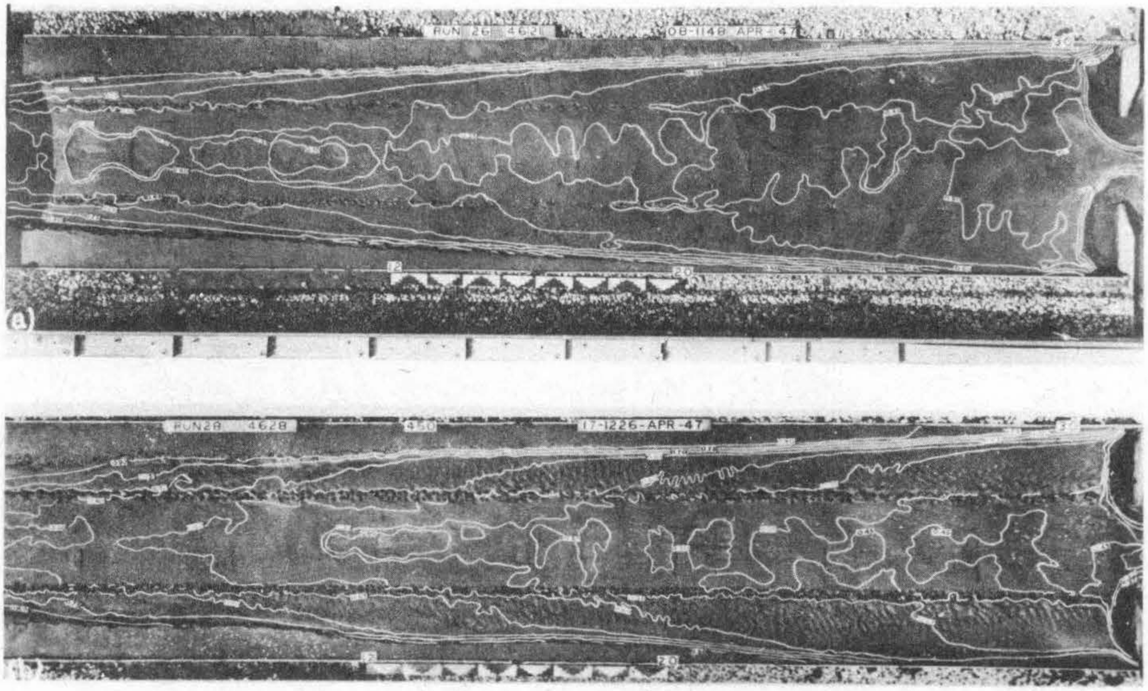


Fig. 20 - COMPARISON OF SCOUR PATTERNS IN CHANNELS REVETED WITH CLOTH TUFTS

See Fig. 12 for details. Tufts covered 100% of wetted bank area at the start of the run. (a) Single cloth tufts. E.R. = 2.3. Note continuously divergent scour pattern. Run #26. (b) Double cloth tufts E.R. = 6.3. Scour pattern indicates that flow was stabilized at about station No. 15. Scour around lower 10 ft may be reaction from wooden terminus. Note tendency to meander. Run #28.

ER was 9.4 and greater than 13.5, respectively, for groins placed at 90° and 45° (pointing downstream) with the flow and spaced along the banks at 2 ft. centers or 0.8 of channel width. It must be remembered that the groins projected 1 inch or about 0.4 of the water depth above the sloping bank at all points, which represented a considerable obstruction to the flow as illustrated vividly in Fig. 21 for flow with the groins alone as revetment.

Extensive widening of the channel was prevented during the effective life of the groins by their action in turning the flow away from the banks at definite points along the channel. The turning, however, resulted in eddying upstream and accelerated flow and eddying downstream which scoured locally the bed and banks around the groin. These disturbances are very noticeable in Fig. 22 as swirls and waves around and off the ends of the groins. It is apparent that the obstruction to the flow and correspondingly, the local scour, is less with the groins pointed downstream than with those set normal to the flow.

The erosion pattern in the channel, before the flow cut around the bank side of the groins, was one of progressive widening between groins as shown in Fig. 22. In this way, the maximum widening was that which occurred between consecutive groins instead of the cumulative sum of all these partial widenings as with the unrevetted channel.

Gradually, however, the widening and local scour increased until the flow was able to break around the bank end of the groin and thereby the effectiveness of the groin was decreased. Then the channel widened progressively throughout its length so that the dikes eventually were breached at the lower end as shown in Fig. 23.

The scour pattern produced with the groins when still keyed into the banks obviously differed from that produced in the unrevetted channel shown with it in Fig. 23. The groin scour pattern is distinctive for the scalloped shape of the banks which are indicative of the stubborn resistance to widening. A notable feature of the scour pattern is the deep hole around the channel end of the groin with its center slightly downstream from the end. In Fig. 23, the pattern presented for the 90° groins is one which existed after the flow had cut

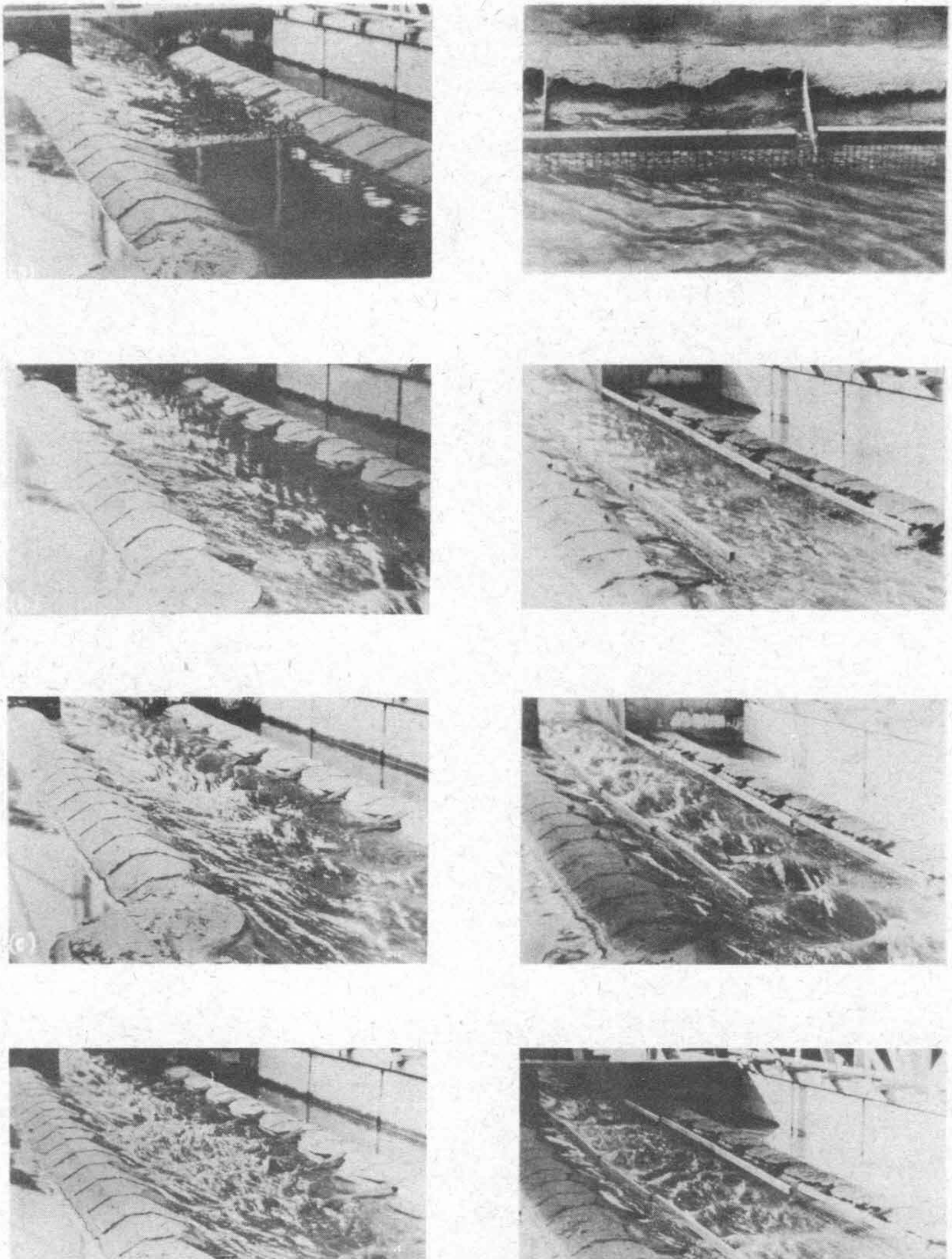


Fig. 21 - PICTORIAL HISTORY OF GROWTH AND BREAKUP OF SAND WAVES IN SOLID GROIN REVETED CHANNEL WITH AND WITHOUT FENCE.

Channel reveted with groins is shown in left column. Channel reveted with groins and 3/4" mesh fence is shown in right column. Groins are solid and are set normal to the flow at 2 ft centers. Flow is 1 cfs. All views, except (a) right, are looking upstream. (a) Initial flow from rest in groin reveted channel and close-up of flow (from left to right) in other channel. (b) Surfaces show undulations due to distortion of bed by sediment movements. Note undercut banks and disturbances off end of groins. (c) Undulations form into wave trains. (d) Waves break upstream. Groins are Run #6 and fence and groins Run #2.

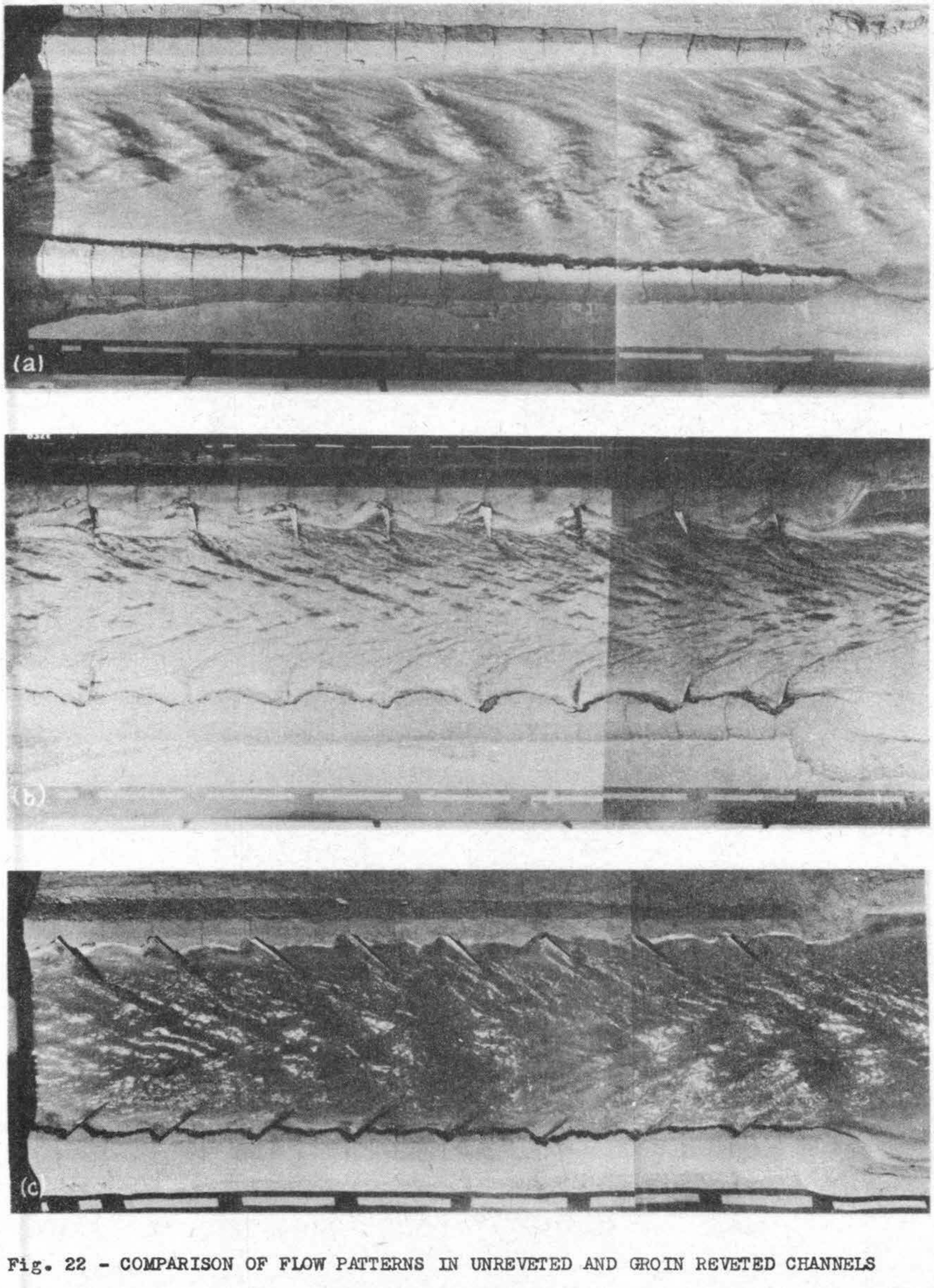


Fig. 22 - COMPARISON OF FLOW PATTERNS IN UNREVETED AND GROIN REVETED CHANNELS

Flow has been continuous for a time equivalent to an effectiveness ratio of about 0.9 in all cases. Groins are solid and spaced at 2 ft centers. Flow is left to right. (a) Unreveted channel. Note divergent scour pattern and sand waves in channel. Run #5. (b) Groins set normal to the flow. Note disturbances off end of groins and eddies around it, and scalloped banks. Run #6. (c) Groins set 45° with the flow. Note relatively small disturbances off the groins and relatively straight banks between groins. Run #7.

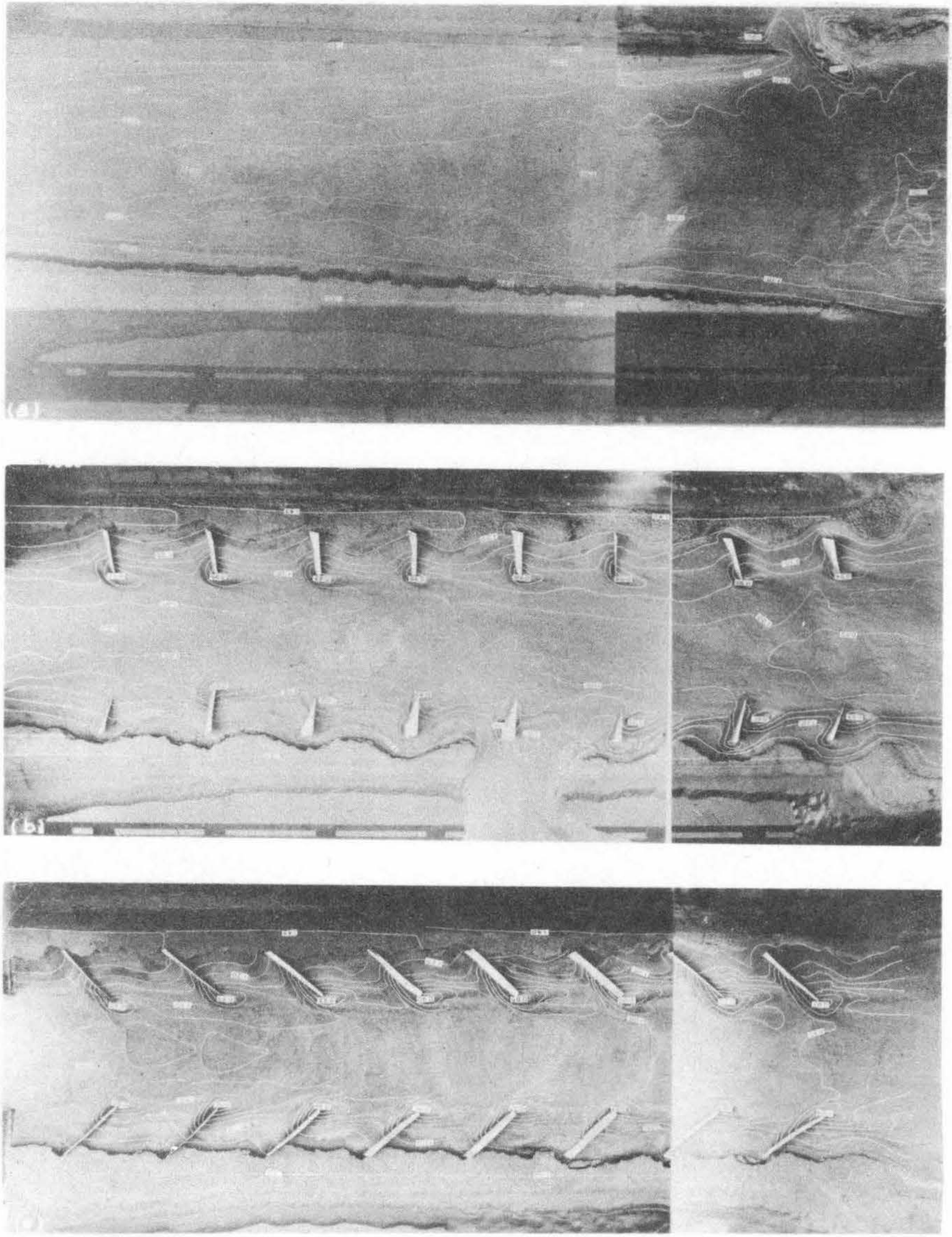


Fig. 23 - COMPARISON OF SCOUR PATTERNS IN UNREVETED AND GROIN REVETED CHANNELS

Groins are solid and spaced at 2 ft centers. Flow is left to right. Contour interval is 0.05 ft. (a) Unreveted channel. E.R. = 1.6. Note divergent banks. Run #5. (b) Groins set normal to flow. E.R. = 9.4. Groins have been undercut and cut around. Note scalloped banks and hole at stream end of groins. Run #6. (c) Groins set at 45° with the flow. E.R. = greater than 13.5. Some of the groins have been undercut and have tipped. Note scour hole at stream end of groin. Run #7.

around the bank end and continued long enough to breach the right bank. The pattern is, therefore, not fully indicative of that which existed before the cut around and the scour hole at the stream end of the groin is considerably filled. The hole indicates the presence of the accelerated flow produced by the obstructing groin in turning the water away from the bank. Note in Fig. 23 that many of the groins have tipped downstream due to erosion of the bank along the downstream face of the groin.

5. Fence with Reinforced Banks

The more elaborate forms of bank revetment were studied in this group of tests. Here the banks had not only a fence in front as a damper and guide wall, but also structures embedded in the sand of the banks to increase their coherence and to shield them against the waves and swirls. The results are presented in Table I.

The effect, as might be expected, was toward a marked increase in bank protection over that provided by either a fence or reinforced banks separately; however, as in the other tests, at no time were the banks free from damage in the form of underminded banks which were eroded progressively as the run continued.

The results in Table II which follow are abridged from those in Table I for the sake of better comparison.

Table II

Effectiveness Ratios for Certain Structures Embedded in The Banks when Used with and without a Single Fence with 3/4 Inch Mesh.

Revetment on the Banks	Status of Fence	
	No Fence	Single Fence
SOLID GROINS		
45° to flow at 2 ft. spacing	>13.5	—
90° to flow at 2 ft. spacing	9.4	>13.5
90° to flow at 4 ft. spacing	—	12.3
TUFTS		
single, over 17% of wetted bank area	—	2.1
single, over 100% of wetted bank area	2.3	5.7
double, over 50% of wetted bank area	—	8.0
double, over 100% of wetted bank area	6.3	>21.9

The addition of the fence permitted the spacing of the groins to be doubled and the coverage of the tufts at least to be halved without a decrease in the amount of protection given the banks. When used with the fence, the groins placed normal to the flow were found to act about as effectively as those pointed downstream at 45° without the fence which may indicate the magnitude of the disturbances produced by the groins set normal to the flow and the ability of the fence to reduce or at least channelize these disturbances.

The extent of the disturbances in the channel and the effect on them of the fence with groins are shown in Figs. 16, 21, and 22. It appears that the fence was able to temper the violence of the disturbances between the stream end of the groins and the banks possibly by reducing the acceleration over the groins and the eddies set up thereby. A comparison of the scour patterns presented in Fig. 17-b and 23-b, particularly along the left (upper) bank, shows that the groins are more in vertical alignment, less tipped, and that the hole at the stream end of the groin is less when the fence is used. All of these tendencies seem to indicate that reduced local scour exists when the fence is used with the groins.

An interesting combination studied under this grouping was that of single permeable groins set in the bank behind a single permeable fence. The groins like the fence were of 3/4 inch mesh fencing and were used as shown in Table I in two runs, number 8 and number 20, which differed only in that the groins were set normal to the flow in the former and at 45° with the flow in the latter. The spacing was 1 ft. or 0.4 of the channel width in both cases. There was no change in effectiveness with attitude of groin, as shown in Table I, and the scour pattern showed a progressive widening, as indicated in Fig. 17. It seems apparent that there was little turning of the flow by these groins since their attitude was not significant and no obvious local scour effects were observed. However, their use did serve to increase the effectiveness ratio from 1.7 with the fence alone to about 4.6. The final channel slope was about double that with the fence alone.

The tufts responded with spectacular increased effectiveness when a fence was placed in front of them so much so that the closest approach to a stable condition was obtained when they were used double over the whole bank area together with the fence (run no. 32). This experiment was terminated after an effectiveness ratio of about 22 was obtained since it was not considered feasible to continue until the slowly eroding banks were breached. The scour patterns are presented in Fig. 24 and are similar in general to those for the tufts alone shown in Fig. 20. It is apparent from the relative serenity of the scour pattern produced with the double tufts and fence (Fig. 24-c) that the attack on the bank was not as severe as that experienced with the double tufts alone, as demonstrated by the battered outlines of the pattern in Fig. 20-b. The fence and tufts were apparently able to confine the expanding flow at a point relatively near to the entrance and to hold it in a more or less uniform channel until the effects of the exit were felt. The resistance offered by the single tufts was not enough to accomplish this for with them and the fence, the channel widened perceptibly throughout its full length.

Pointed evidence of the superior effectiveness of groins over a continuous fence (3/4 inch mesh) is given in Fig. 25, which shows the active channel revetted on the right bank with a fence and on the left bank by a similar fence backed by solid groins set normal to the flow at 1 ft. spacing or 0.4 of the channel width. It will be noted that after continuous flow for a time equivalent to an effectiveness ratio of 0.3 the bank behind the fence alone has been widened about one-half the channel width at the lower end while that behind the fence with groins has only expanded about one quarter the width. In addition the right bank shows severe caving and nearly sheer banks while those on the left show less caving and a more gradual slope. The standing wave patterns appear to be of about equal magnitude along the channel side of both banks.

E. Review of Performance-The Channel with Various Revetments

The effectiveness of the various revetments studied is presented in the form of bar graphs in Fig. 26. It is apparent that the mesh fence generally increased the ability of the bare banks and of any revetment embedded in them to contain the flow within the sand channel. In some cases, the increase was small and may not have warranted the

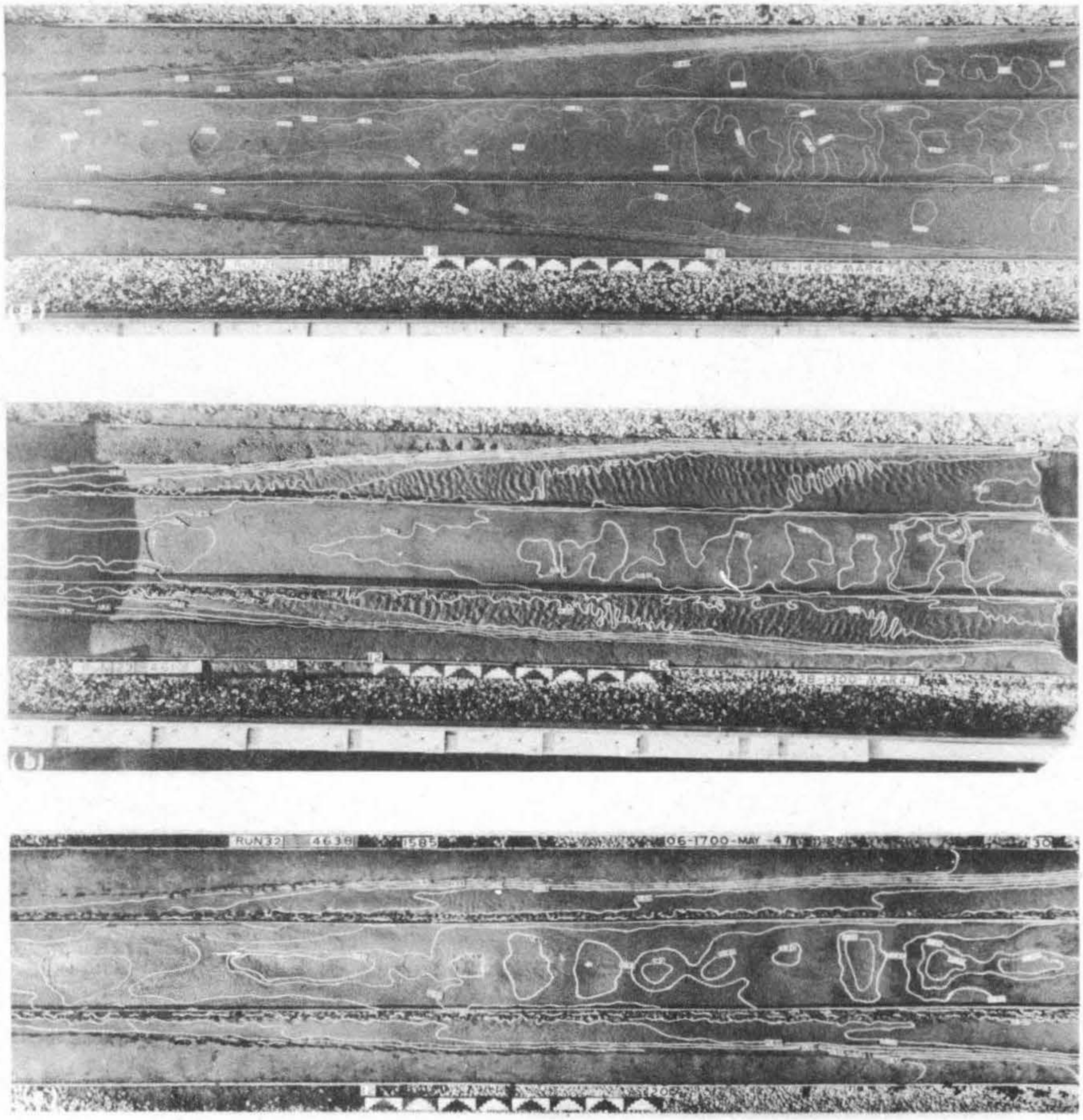


Fig. 24 - COMPARISON OF SCOUR PATTERNS IN FENCE REVETED CHANNEL WITH AND WITHOUT CLOTH TUFTS ON THE BANKS

Fence is 3/4" mesh and tufts covered 100% of the wetted bank area at the start of the run. Flow was left to right. (a) Fence alone. E.R. is 1.8. Pattern is typically divergent in the direction of flow and generally symmetrical about the centerline. Run #37. (b) Fence with single tufts on the bank. E.R. is 5.7. Channel divergence appears to have been completed beginning about station 15, especially along the right bank. Run #23. (c) Fence with double tufts. E. R. is greater than 21.9. Channel divergence appears to have been completed beginning at about station 15. Run #32.

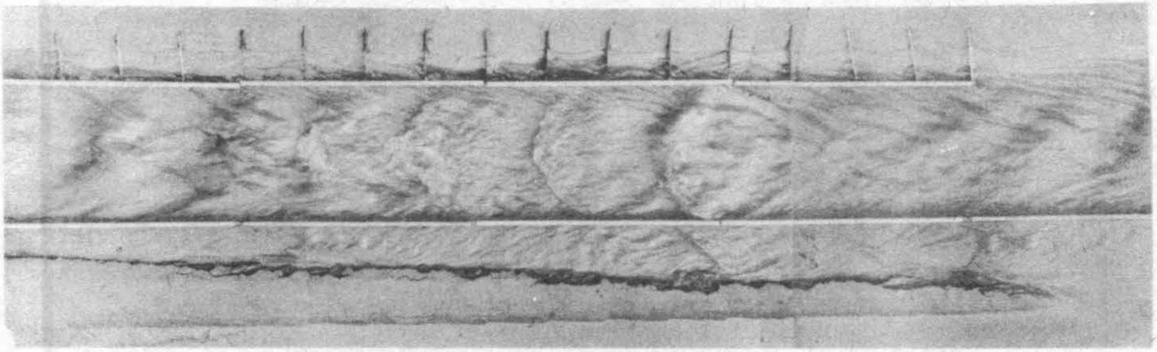


Fig. 25 - FLOW PATTERN IN CHANNEL REVETED ON LEFT BANK BY A FENCE AND ON RIGHT BANK BY FENCE AND GROIN

Fence is 3/4" mesh and groins are solid and set normal to the flow at 1 ft spacing. Run #14. Pattern shown is that after a continuous flow equivalent to an effectiveness ratio of 0.3. The difference in bank scour is obvious. The groins evidently increased the disturbances along the right bank for effectiveness ratio dropped from 1.7 with fence on BOTH banks to the 0.75 as shown here.

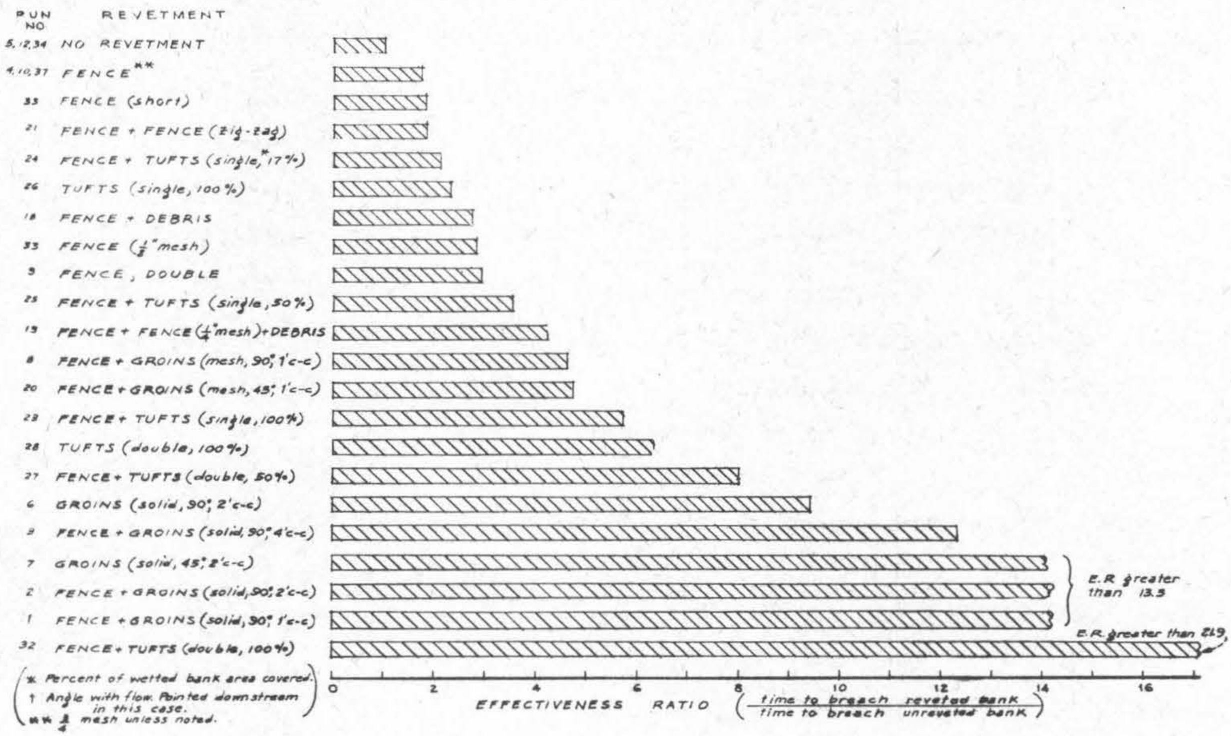


Fig. 26 - RELATIVE EFFECTIVENESS OF VARIOUS REVETMENTS TESTED AS SHOWN BY BAR GRAPHS

Data are taken from Table I.

additional structures, as for instance, the zig-zag fence added to a fence along the toe of the slope. Some of the most spectacular increases were those which accompanied the addition of a fence to a channel with vegetated banks (single and double tufts) or with solid groins.

Meandering was noticeable only during a few of the runs, for example, run no. 28, as illustrated in Fig. 20-b. Tiffany and Nelson state (7):

> "A preliminary test (in a sand channel) established the fact that an initially straight channel, without any disturbing factors to cause a deflection of the directive force of the water, would remain straight."

However, it seems apparent that water flowing in a straight line is inherently unstable and therefore if the channel used in these tests had been longer, the meandering would have been more noticeable.

Progressive widening of the channel between control points (solid groins or the channel termini) was very noticeable during all the runs. This was particularly apparent when the unrevetted channel was being studied or when a continuous pervious revetment was used, such as the fence or widely-spaced tufts. In these cases the flow had the full length of the channel to expand into without being contracted at intermediate points by groins.

It appears that this widening is a natural adjustment of the flow to the erodible test channel. If the test channel were very long, the expansion undoubtedly would continue until the lateral components of the turbulent flow forces were balanced by the reactions of the banks, at which time the expansion (widening) would stop and parallel banks would result. The test channel was much too short for any such condition to be realized with the very pervious forms of revetment previously mentioned.

Solid groins forced the flow through non-erodible sections at definite intervals and thereby limited the widening to that which occurred between groins. In a few cases with simulated vegetation, the expansion appeared to have been fully completed within the length of the channel even though the lapping of the water was enough to produce increased widening and eventually failure of the banks. This stabilization was most apparent in run no. 32 as shown in Fig. 24-c where the banks were strongly revetted with a 3/4" mesh fence backed by double cloth tufts over 100% of the wetted bank area at the start of the run. After a continuous flow equivalent to an effectiveness ratio of about 22, the widening appeared completed at a section about one-third of the way down the channel. Thereafter, for another one-third of the channel length, the channel width was effectively constant. The fact that the pattern in Fig. 24-c exhibits a second wide section downstream from the first is no doubt due to the disturbances produced by eddying upstream from the solid terminus.

It was noted under the report on the performance of the revetments (section IV-D) that the solid groins when placed normal to the flow produced a greater disturbance than those pointed downstream and at an angle of 45° as shown in Fig. 22. Time was not available for study of the groins at other angles. However, Rouse (8) has treated a similar problem, that of high velocity flow at an abrupt bend. He shows, for example, that for a given Froude Number[1] greater than 1 as in these tests, the ratio of the depth of water downstream from the bend to that upstream from the bend increases with the angle of the bend from 0 to 90 degrees. The condition for angles greater than 90° (where the bend or groins would point upstream) was not discussed. The reference cited can not be strictly applied to the groins as used since it is concerned with approach conditions that are uniform. However, it does serve to indicate the trend in the magnitude of the disturbance induced by the bend.

It will be noted in Table I that the final channel slopes do not vary in the same manner as the effectiveness ratios of the revetments. The channel with revetted banks always showed a higher slope than the unrevetted channel. Debris on the fence produced the maximum slope in the channel. The solid groins showed a surprisingly low slope when used alone, but this increased considerably when the fence was added to the groins. The tufts alone gave a slope that was about the same

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[1]Froude Number $F = \frac{V}{\sqrt{gd}}$ where V equals velocity, d equals depth and g equals the acceleration due to gravity.

as that when they were used with the fence.

The slope values in Table I cannot be taken as direct indications of the relative roughness of the various revetments since all the variations may not be due to this factor but they are a qualitative comparison of the action of the revetments on the bottom slope which can be measured against the effectiveness of the revetment.

The slope of the channel bed is indicative, generally, of the sediment-transporting capacity of the channel. As long as the sediment transportation is constant, then the channel with the highest slope has the least sediment-transporting capacity. That is, such a channel so restricts the transportation that the slope has to be increased so that the flow can push the required load through the channel. In these experiments, the rate of discharge was kept constant, but the transported load varied and, therefore, the closed system adjusted itself until the load, as regulated by the revetted test channel, was the same throughout the whole system for any one revetted condition. This adjusted slope was generally much less than if the sediment load had been kept constant.

F. Conclusions

Following are conclusions based on laboratory experiments in a trapezoidal sand channel 2 1/2 ft. wide containing sand-laden flow at 1 cfs. at a depth of about 0.2 ft. The fence referred to is one extending well above the water line with wire fencing whose mesh (3/4") is 0.3 of the water depth unless otherwise stated.

1. The channel revetted with a single fence was nearly twice as effective in containing the flow as without the revetment. When the fence was doubled or when the mesh in the single fence was reduced from 3/4" to 1/8", the channel was nearly 3 times more effective than without the revetment.

2. The channel revetted with solid metal groins spaced at 2 ft. centers along both banks was 10 to greater than 14 times more effective in containing the flow than without the revetment, depending on whether the groins were placed respectively normal to or 45° with the flow pointing downstream.

3. The channel revetted with one layer of simulated vegetation over the complete wetted bank area was twice as effective in containing the flow as without the revetment. When the simulated vegetation was doubled, the channel was greater than 6 times more effective in containing the flow than without the revetment.

4. The channel revetted with a single fence and solid groins placed normal to the flow at 4 ft. and 1 ft. centers along both banks was respectively 12 to greater than 14 times more effective in containing the flow than without the revetment. The effectiveness of the channel increased when the attitude of the groins was changed from normal to 45° with the flow pointing downstream.

5. The channel revetted with a single fence and pervious (mesh) groins placed normal to the flow at 1 ft. centers along both banks was about 5 times more effective in containing the flow than without the revetment. The effectiveness of the channel was not changed when the attitude of the groins was changed from normal to 45° with the flow pointing downstream.

6. The channel revetted with a single fence and one layer of simulated vegetation over the whole of the wetted bank area was 6 times more effective in containing the flow than without the revetment. The degree of effectiveness increased to greater than 22 times when the vegetation was doubled. When the bank coverage was decreased, the effectiveness of the revetment decreased.

7. The channel revetted with a fence with simulated debris attached was 1 1/2 times more effective in containing the flow than the channel revetted with the fence alone.

8. The revetted channels generally had transported sand loads which were less than the load in the unrevetted channel. This tendency is reflected in the final channel slopes which were always greater in the revetted channels than in the unrevetted channel. Thus, an increase in the roughness of the banks due to addition of revetment decreased the sediment-transporting capacity of the channel.

9. Solid groins obstructed the channel flow at definite intervals regulated by their spacing, and thereby caused conspicuous standing waves to form. The magnitude of these standing waves was greater with

groins set normal to the flow than with those pointed downstream at an angle of 45°. The presence of the waves was reflected in the scour pattern produced.

10. During discharge, the test channel tended to widen progressively in the direction of flow between control points. These points, depending on the revetment used, were the channel termini, solid groins or even simulated vegetation when used in a sufficient concentration.

11. Pervious groins increased the effectiveness of the channel to contain the flow but they did not alter the general progressive pattern of widening.

12. The most apparent attack on the banks was in the form of generally lateral wave disturbances which constantly beat against the banks and thereby caused undermining and caving. The disturbances were produced by the general rise and fall of the unsteady high flow, and primarily by the "sand waves" which formed and eventually broke on the surface and against the banks.

13. A fence of about 1/2 water depth in height proved as effective as one extending well above the water line. This may indicate that the erosive forces may be damped sufficiently by a submerged fence or under water barrage although this question was not fully investigated.

V. CONCLUSIONS FROM FIELD AND LABORATORY STUDIES

Following are conclusions based upon a consideration of the existing field installations in the light of the results obtained from the laboratory tests in the fully erodible channel with sand-laden flow. The conclusions are limited to the likely behavior of the revetments in a tangent section of a stream.

1. Fence revetments as constructed in Southern California, can be expected to give considerable protection to the channel banks. It is not possible to give a quantitative value for the amount of protection since it will vary, for instance, with the size of the mesh of the fencing, the depth of the water, the location of the fence in the channel, the amount of debris present, and the like.

2. A fence covered with debris or backed up with brush, can be expected to give much more protection to the banks than the fence alone.

3. Vegetation planted on the channel banks should add considerably to their protection. For best results, the vegetation should be dense and deep rooted so that it may resist the scour forces even when partially uprooted by undermining of the bank.

4. Groins of impervious construction should give much more protection to the channel banks than those constructed of pervious materials.

5. Groins of impervious construction placed at 45° with the flow and pointing downstream should give much more protection to the banks than those placed normal to the flow.

6. Considerable local scour may be expected around the impervious type of groins; therefore, the structures should be constructed deep enough into the channel bed and bank and otherwise protected from undermining by this scour.

7. There should be less local scour around both the stream and bank ends of the groin if they are pointed downstream rather than placed normal to the flow. An angle of 45° with the flow should be a reasonable angle for groins pointed downstream.

8. It may be expected that revetment such as fences, groins, and vegetation, will cause the slope of the channel bed to increase over that of the unrevetted channel provided there is no great change in the sediment load being brought into the revetted channel.

APPENDIX I

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APPENDIX 2A

COST OF SINGLE PIPE AND WIRE FENCE

(6 ft. high, one-half braced and 500 ft. long (from files of Los Angeles County Flood Control Dist. Costs are in 1946 dollars.)

Pipe and Wire Protection		Unit Cost	Total Cost	Per Lin. Ft.
Foreman 6 shifts incl. moving	at	$15.00	$90.00	$0.18
Hand excavation 35 c.y.	at	1.40	49.00	0.098
Hand backfill 20 c.y.	at	0.80	24.00	0.048
Place fence 500 lin. ft.	at	0.30	150.00	0.30
Miscellaneous labor 500 lin. ft.	at	0.02	10.00	0.02
			$323.00	$0.646
Materials				
520' - 72" welded wire fencing	at	0.12	62.40	0.125
64 pairs 2 1/4" x 12'- 0" boiler tubes	at	1.75	112.00	0.224
37 pairs 2 1/4" x 10' -0" " "	at	1.40	51.80	0.104
No 9 Ga. galv.tie wire 15 lbs.	at	0.05	0.75	0.0015
No 12 Ga. galv.tie wire 50 lbs	at	0.05	2.25	0.0045
Miscellaneous materials	at		5.00	0.01
			234.20	0.468
Total Work Items			$557.20	$1.114
Incidentals				
Warehouse charge $234.00	at	10%	23.42	
Photographs and blueprints			5.00	
Use of District small tools $323.00	at	1%	3.23	
Hauling (50 mi. R.T.)			25.00	
Vacations, etc. $323.00	at	10%	32.30	
Compensation Insurance $323.00	at	5%	16.15	
Contingencies $550.00	at	5%	27.50	
			132.60	$0.265
Subtotal			689.80	1.38
16% overhead			110.37	0.22
TOTAL ESTIMATE			$800.17	$1.60

APPENDIX 2B

COST OF DOUBLE PIPE AND WIRE FENCE

(6 ft. high, one-half braced and 500 ft. long (from files of Los Angeles County Flood Control Dist. Costs are in 1946 dollars.)

Pipe and Wire Protection		Unit Cost	Total Cost	Per Lin. Ft.
Foreman 9 shifts incl. moving	at	$15.00	$135.00	$ 0.27
Hand excavation 65 c.y.	at	1.40	91.00	0.182
Hand backfill 60 c.y.	at	0.80	48.00	0.096
Place Fence 500 lin. ft.	at	0.545	272.50	0.545
Miscellaneous labor 500 lin. ft.	at	0.03	15.00	0.03
			$561.50	$1.123
Materials				
1040 ft - 72" welded wire fencing	at	0.12	124.00	0.25
128 pcs 2 1/4"x12' boiler tube	at	1.75	224.00	0.448
41 pcs 2 1/4"x10' boiler tube	at	1.40	57.40	0.115
64 pcs 2 1/4"x1'4" boiler tube	at	0.15	9.60	0.019
No. 9, Ga. galv. tie wire 50 lbs	at	0.05	2.25	0.0045
No. 12, Ga. galv. tie wire 100 lbs	at	0.05	5.00	0.01
No. 14, Ga. galv. tie wire 20 lbs	at	0.05	1.00	0.002
Miscellaneous materials			5.00	.01
			429.05	0.858
		Total Work Items	$990.55	$1.981
Incidentals				
Warehouse charge $429.05 at	10%		43.91	
Photos and blueprints			5.00	
Use of District small tools $561.50	1%		5.62	
Hauling (50 mi. R.T.)			25.00	
Vacations etc. $561.50	10%		56.15	
Compensation Insurance $561.50	5%		28.08	
Contingencies $990.00	5%		49.50	
			212.26	0.425
		Subtotal	1,202.81	2.41
		16% overhead	192.45	0.385
		TOTAL ESTIMATE	$1,395.26	$2.79